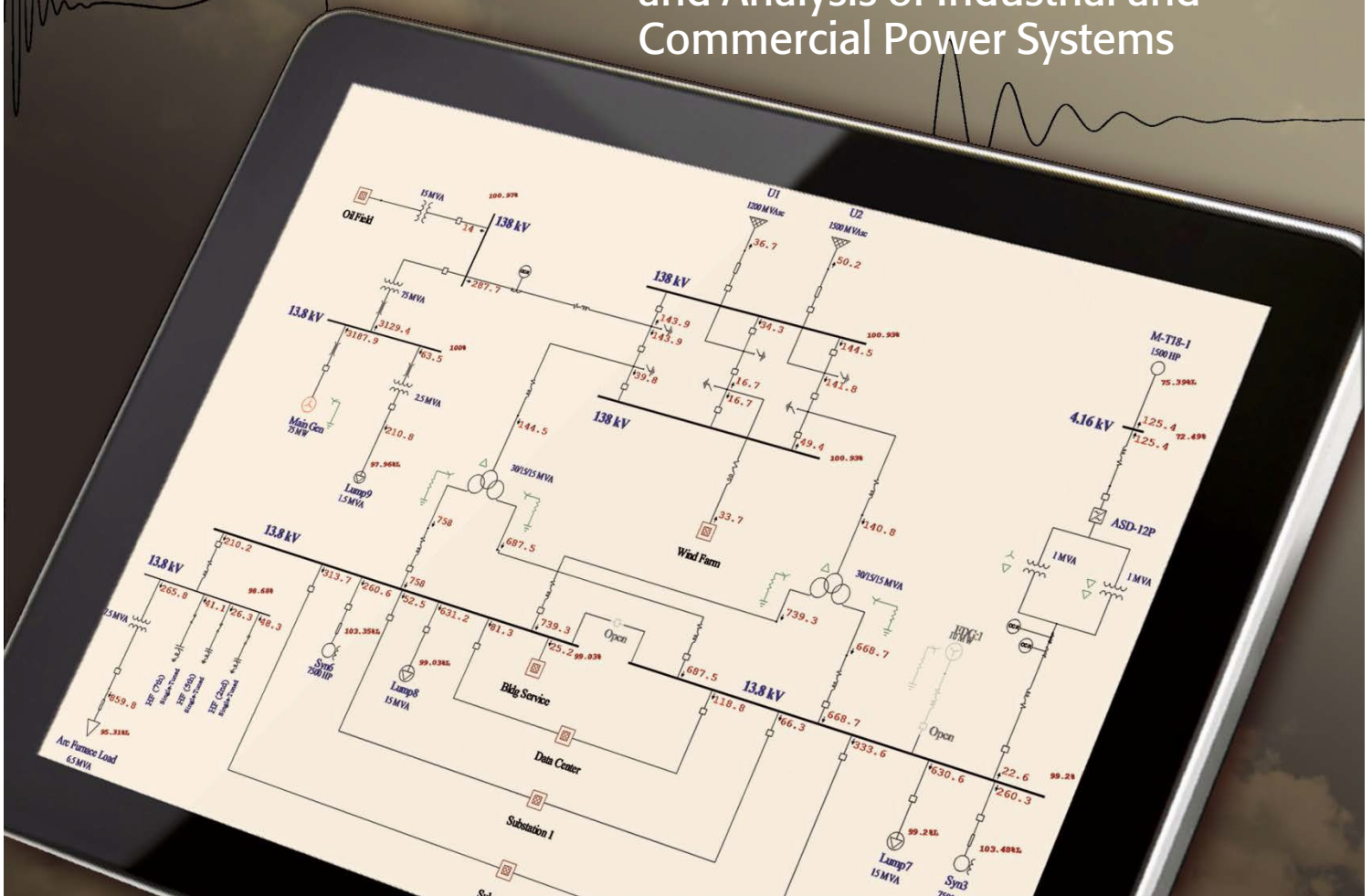


IEEE Std 3002.2™-2018

Recommended Practice for Conducting Load-Flow Studies and Analysis of Industrial and Commercial Power Systems



IEEE Recommended Practice for Conducting Load-Flow Studies and Analysis of Industrial and Commercial Power Systems

Sponsor

Technical Books Coordinating Committee
of the
IEEE Industry Applications Society

Approved 27 September 2018

IEEE-SA Standards Board

Abstract: Activities related to load flow analysis, including design considerations for new systems, analytical studies for existing systems, as well as operational and model validation considerations for industrial and commercial power systems are addressed. Load flow analysis includes steady-state power flow and voltage analysis along with considerations for optimal power flow calculations. The use of computer-aided analysis software, with a list of desirable capabilities recommended to conduct a modern load-flow study, is emphasized. Examples of system data requirements and result analysis techniques are presented.

Keywords: cable ampacity, compensation, convergence, demand factor, electrical losses, Gauss-Seidel, generation, IEEE 3002.2, impedance, industrial loads, industrial power system, load flow analysis, load-flow studies, Newton-Raphson, overload, over voltage, power demand, power factor correction, power flow, system validation, under voltage, voltage drop, voltage profile, voltage rise

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Introduction

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When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3002.2™

This recommended practice describes how to conduct load-flow studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the analysis of the operation of industrial and commercial power systems.

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IEEE Recommended Practice for Conducting Load-Flow Studies and Analysis of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to conduct load-flow studies and analysis for industrial and commercial power systems. It will be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 399™-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (*IEEE Brown Book™*).^{1,2}

3. Introduction

Load flow is also referred to as *power flow*; these terms may be interchangeably used in this standard. This is the name given to a network solution that predicts steady-state currents, voltages, and real and reactive power flows through every branch and bus in the system. Load-flow studies simulate operating conditions that cannot practically be experienced on the actual system because the system has not yet been built, because of the practical constraints of time, or because it would be unwise to expose the actual physical system to conditions that are potentially damaging. The end objective of the load-flow study is not always to arrive at hard, numerical performance parameters. Often the objective is to gain insight into how the system performs over a range of operating conditions. Power flows are an important part of power system operation and planning.

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Because the parameters of the elements such as transmission and distribution lines, cables, and transformers are constant, the power system network impedance is for the most part fixed. However, the power flow problem often involves constant kVA loads, generators, and tap changers, which then means that the relationship between voltage and current changes depending on the type of load. The same holds true for the relationship between the real and reactive power consumption at a bus, or the generated real power and scheduled voltage magnitude at a generator bus. Thus, power flow calculation involves the solution of a set of equations which involve loads of constant impedance, constant power, and sometimes constant current type. This power flow calculation gives the electrical response of the power system to a particular set of loading and supply power output.

4. Analysis objectives

One of the most common computational procedures used in power system analysis is the load flow calculation. The planning, design, and operation of power systems require such calculations to analyze the steady-state (quiescent) performance of the power system under various operating conditions and to study the effects of changes in equipment configuration. Typical results from steady-state load flow analysis include power flow in each branch circuits, source loading, voltage magnitude, phase angles, etc.

For some types of equipment (e.g., photovoltaic solar arrays or wind farms), a time varying simulation, such as a time domain load flow, may be required in order to fully understand the behavior of the electrical system over a period of time. These time varying load flow solutions are performed using computer programs designed specifically for this purpose.

Analyzing the solution of this problem for numerous conditions helps ensure that the power system is designed to satisfy its performance criteria while incurring the most favorable investment and operation costs.

Some examples of the uses of load-flow studies are to determine the following:

- Component or circuit loadings
- Steady-state bus voltages
- Real and reactive power flows
- Transformer tap settings and load tap changer actions
- System real and reactive power losses and voltage drops
- Real and reactive power demand and voltage drop at utility source connection
- Generator exciter/regulator voltage set points
- Undervoltage and overvoltage conditions for buses as well as equipment terminals
- Performance under maximum, normal, minimum, and startup loading conditions
- Performance under various operating configurations (such as co-gen on or off, tie-breakers closed, etc.)
- Performance under emergency conditions (post-contingency)
- Requirement for either fixed or variable power factor improvement equipment

Load flow analysis has a great importance:

- a) To verify the operation of a network under various load and generation conditions
- b) To plan the future growth of both loads and generation

- c) To determine the best economical operation for existing systems
- d) To establish initial conditions for stability studies
- e) To help identify the need for additional capacitive or inductive VAR support, to maintain system voltages within acceptable limits

Also, load flow results are very valuable for setting the proper protective devices to avoid nuisance tripping and improve system reliability. In order to perform a load-flow study, full data must be provided about the studied system, including one-line diagram, parameters of transformers, cables and transmission lines, rated values of each equipment, and the real and reactive power for each load.

Modern systems may be complex and have many paths or branches over which power can flow. Such systems form networks of series and parallel paths. Electric power flow in these networks divides among the branches until a balance is reached in accordance with Kirchhoff's laws.

There are generally two types of computer load flow programs—those intended for offline planning purposes, and those designed to operate in real-time, actively receiving input from the actual system. Most load flow planning studies use off-line software. On-line, or real-time load flows incorporate data input from the actual networks and can bridge the gap between static/planning network model and the model used by those responsible for actual system operation. Computer programs are also available that provide integrated off-line and real-time solutions for “what if” predictive analysis. Such systems are able to integrate with existing plant Supervisory Control and Data Acquisition (SCADA) systems. Integrated real-time systems can therefore be used as planning and design tools as well as a dispatching tool for the operator. And an additional level of sophistication is possible using so-called “optimal power flow” modeling that applies constraints in the load flow solution to achieve objectives, such as minimum fuel cost, minimum power loss, flat voltage profile, etc.

For industrial and commercial power systems, the load flow problem involves balanced, steady-state operation. Hence a single-phase, positive sequence model of the power system is typically sufficient. Three-phase or unbalanced load flow analysis software is available, but is rarely needed in industrial power system applications.

A load flow calculation determines the state of the power system for a given load and generation distribution. It represents a steady-state condition as if that condition had been held fixed for some time. There are situations in industrial applications where the issues of interest involve how those steady-state conditions change over periods of minutes to hours as a consequence of changes in loading or generation; these applications can be adequately simulated using conventional load flow tools by means of a series of simulations reflecting the pertinent changes. However, this kind of study may also be accomplished by utilizing a time-domain load flow program. On the other hand, concerns about how systems respond in the cycles-to-seconds time frame, perhaps as a consequence of short-circuits or other disturbances, should be addressed using dynamic stability software. Power system dynamic stability is beyond the scope of this document.

In actuality, branch flows and bus voltages constantly fluctuate by small amounts because loads change constantly (e.g., lights, motors, and other loads are turned on and off). Engineers responsible for analysis shall understand the switching pattern and its implications, and may choose to ignore this while calculating the steady-state effects on system equipment.

As the load distribution, and possibly the network, will vary considerably during different time periods, it may be necessary to obtain load flow solutions representing different system conditions such as peak load, average load, or light load. These solutions will be used to determine either optimum operating modes for normal conditions, such as the proper setting of voltage control devices, or how the system will respond to abnormal conditions, such as branch or transformer outages. Load flows form the basis for the determination of new equipment additions, effectiveness of alternatives to solve present deficiencies, and how to meet future system requirements.

The load flow model is also the basis for several other types of studies such as short-circuit, stability, motor starting, and harmonic studies. The load flow model supplies the network data and provides an initial steady-state condition for these studies.

5. System simulation and modeling

5.1 Modeling requirements

Industrial plant electrical systems can be extensive. A simplified visual means of representing the complete system is essential to understanding the operation of the system under its various possible operating modes. The system one-line diagram serves this purpose. The one-line diagram represents the actual phase and neutral conductors of single-phase, two-phase, and three-phase ac systems (two, three, and four wires) with a single conductor, identifying switchgears, motor control centers, loads, generators, capacitors, and interconnecting lines, cables, transformers, reactors, variable frequency drives, etc. In order to analyze any network, we use reference points that are electrically distinct; that is, there is some impedance between them which can sustain a potential difference, or switching devices between them. These reference points are called *nodes* and *buses* in this document. Buses represent a junction in the system at which the power either flows in or out of equipment, such as a motor control center (MCC) or switchgear. Nodes are the points at which the outcome of analysis is of interest, such as transformer or motor terminals.

The drawing format will vary depending on the computer programs used and the preference of the users, but the one-line diagram should give the necessary network and equipment information in a clear, concise manner. The transfer of this data to the load flow program for analysis is discussed in [Clause 6](#).

It is necessary to know equipment parameters as well as their relationship to each other. Depending on the computer program being used, parameters may be either displayed directly on the one-line diagram, or may be listed in tables that accompany that diagram. [Figure 1](#) is an example one-line diagram that will be used throughout this standard to illustrate some aspects of load-flow studies.

Bus names (typically equipment tags or numbers) are displayed along with the bus nominal voltages. Interconnecting lines are usually shown with their impedance values and lengths entered. Equipment associated with a bus is shown connected to that bus. For instance, generators are shown connected to their bus with their equipment parameters specified, as illustrated in [Figure 1](#) and [Figure 8](#). Similarly, loads are shown connected to Bus 2A in [Figure 6](#). Motor loads may be indicated separately (such as MCCs) or combined into one equivalent motor (“lumped”) based on their size and quantity. Most software programs have the requirement of having branch elements—such as transmission lines, cables, and transformers—be connected between two buses. As depicted in [Figure 1](#), the bus can be displayed as a node or a bus, depending on the connection type and the equipment being represented by the bus. As an example, a bus connected between the feeder cable and a transformer is typically displayed as a node, while a bus connected to the secondary load side of a transformer is most often represented as a bus (which may represent a switchgear, panel, MCC, etc.). Lastly, information to convey an off-nominal turns ratio should be given when applicable (e.g., tap settings, voltage regulator position, etc.).

5.2 Overall description of industrial/commercial power system example

The sample system created to illustrate the process of performing a load flow analysis contains portions of different types of components which can be encountered in different heavy and light industrial power systems and/or commercial installations. [Figure 1](#) below shows the example system. The system contains the following component types:

- High-voltage switchyard (heavy industrial facilities may own and be responsible for this part of the system).

- Medium-voltage power distribution switchgear with multiple source feeders (common to large refineries and process driven facilities).
- Larger generation or co-generation plants, with a dedicated unit transformer (~75+ MW capacity).
- Smaller generation equipment (emergency, stand-by, and co-generation).
- Double-ended secondary selective medium- and low-voltage switchgear configurations.
- Emergency and critical systems (similar to “tier 1” or “small” datacenter configurations). Larger industrial/commercial facilities may have data backup requirements with uninterruptible power supply (UPS) units.
- Large arc-furnace loads and harmonic filter(s) similar to what may be found in large steel manufacturing plants. Use appropriate model components from the software which simulate the power factor correction and harmonic load flow content matching the characteristics of such equipment.
- Synchronous motor with excitation system control configurable to voltage or power factor support.
- Adjustable speed drives (ASDs) or variable frequency drives (VFDs) may be used for a variety of induction/synchronous motor controls.
- Example of microgrid application which includes renewable energy sources like photovoltaic (PV) installations which may be connected through converters.
- Wind turbine generation which can take advantage of renewable energy sources. The wind turbine system is an example of distributed generation load flow simulations.

The one-line diagram in [Figure 1](#) does not represent an actual installation that combines all of the individual components listed above. This example was designed to be an educational tool for explaining load flow concepts that otherwise would not be encountered in typical industrial/commercial installations. Furthermore, the intent of the example system used in this chapter is not to represent “best design practices” of industrial and commercial power systems.

Note that the example also contains multi-frequency components but no one-phase ac or dc elements. In an actual industrial complex, building loads are often included and modeled as lumped loads. For simplicity they are not included in this example.

[Figure 2](#) through [Figure 9](#) show individual components included inside “composite networks” or components located in other areas of the drawing via “remote connectors.” The composite networks are elements which represent a sub-layer (or nested view) of elements. The remote connectors are symbols which allow the omission of the connecting line between two elements. These elements do not represent a real-life component, but are used mainly to simplify the one-line drawing. The following describes the connections through these elements:

- The contents of the composite networks “Oil & Gas,” “Substation1,” and “Data Center” are shown in [Figure 2](#), [Figure 6](#), and [Figure 7](#), respectively.
- The elements connected through remote connectors “Arc Furnace Feeder” and “Sub Pump Feeder” are shown in [Figure 4](#) and [Figure 5](#), respectively.

Computer programs utilize several drawing symbols that often do not have equivalents in IEEE Std 315™-1993. Even if a symbol is available in IEEE standards, computer programs may not draw exactly as shown. The reasons are:

- The standard symbol is not complex enough to visually convey technical details about the component.
- IEEE standards may not be up to date with technology, or the symbol are specific to the program.

- Compound elements (i.e., lumped loads, PV arrays, etc.) require more than one symbol for their representation. Software packages may use alternate “compound symbols” to simplify the drawing.

The previous reasons explain why most software packages may not use a standardized set of symbols. Details on the power system analysis software drawing symbols used in this example are presented in [Table B.14](#).

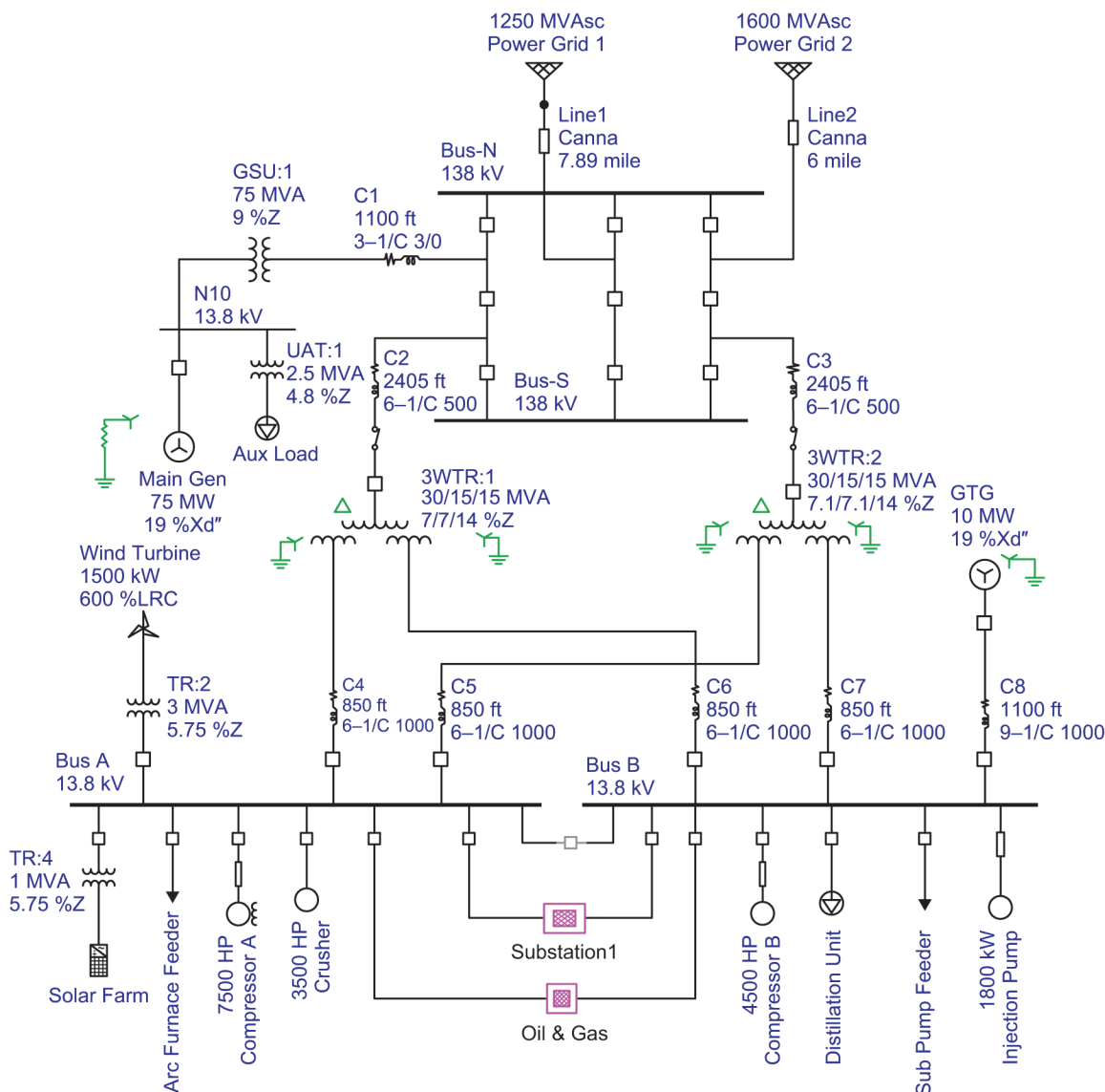


Figure 1—Load flow example system one-line diagram (IEEE 3002 system)

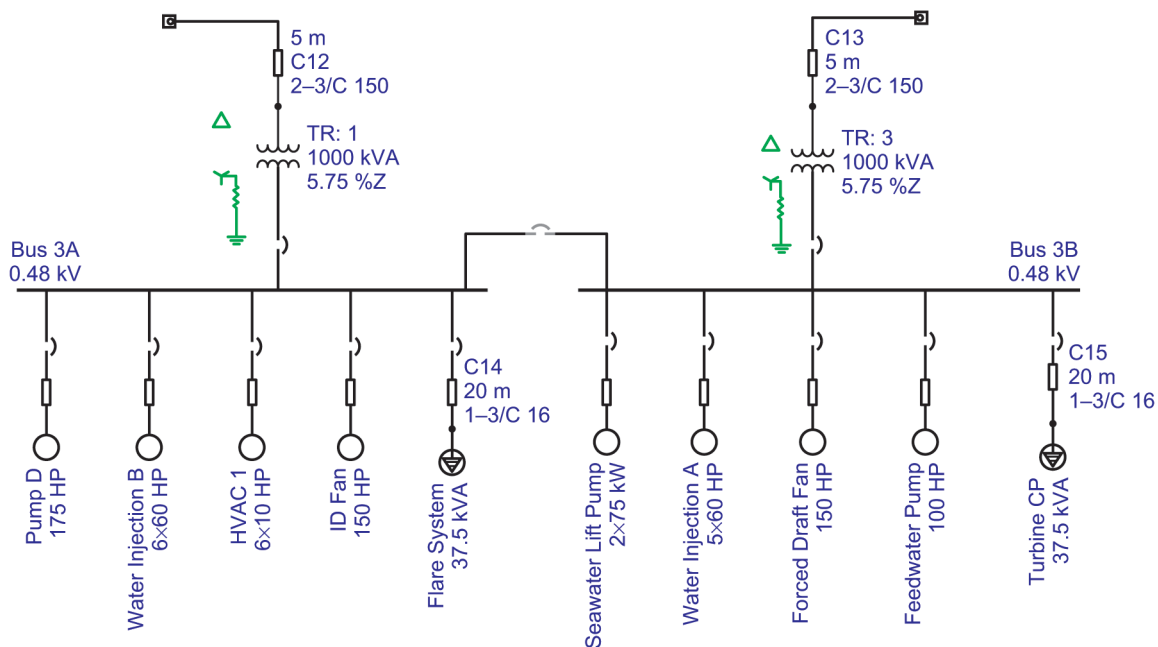


Figure 2—One-line diagram for “Oil & Gas” substation

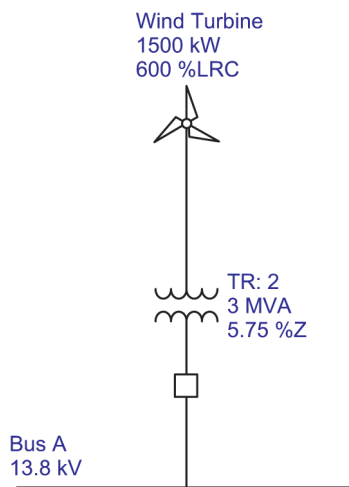


Figure 3—One-line diagram of the wind turbine

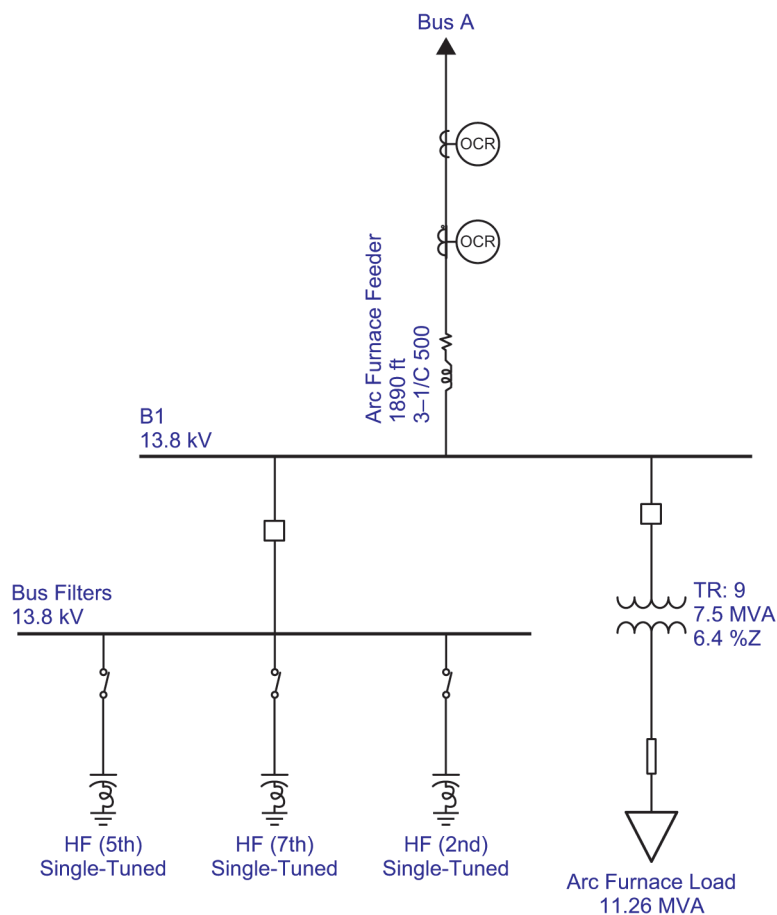


Figure 4—One-line diagram of the arc furnace components

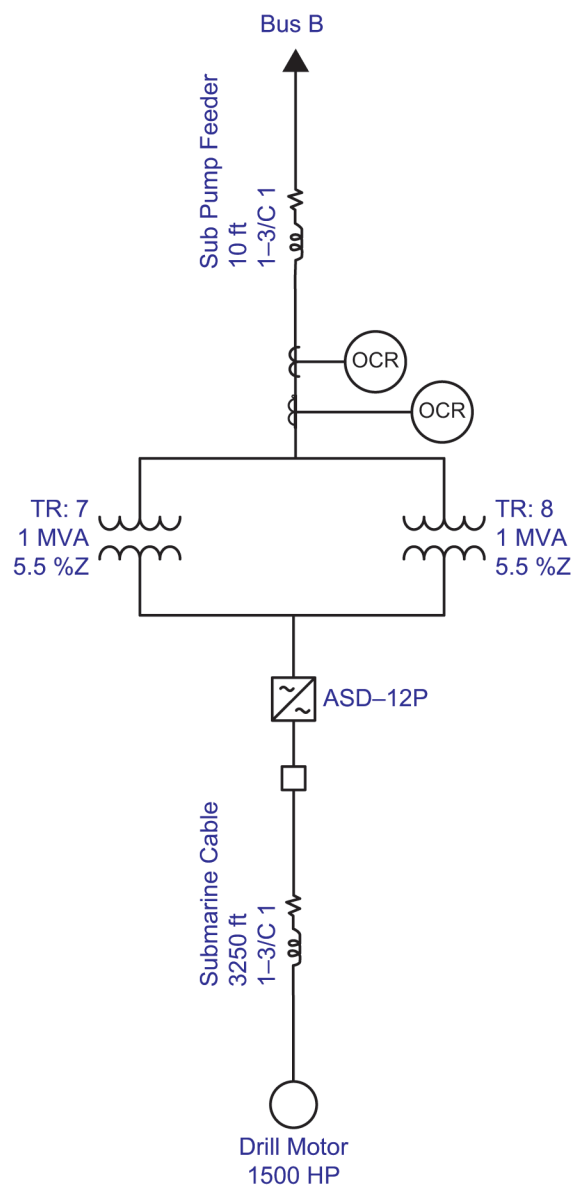


Figure 5—One-line diagram of the ASD-driven submarine system

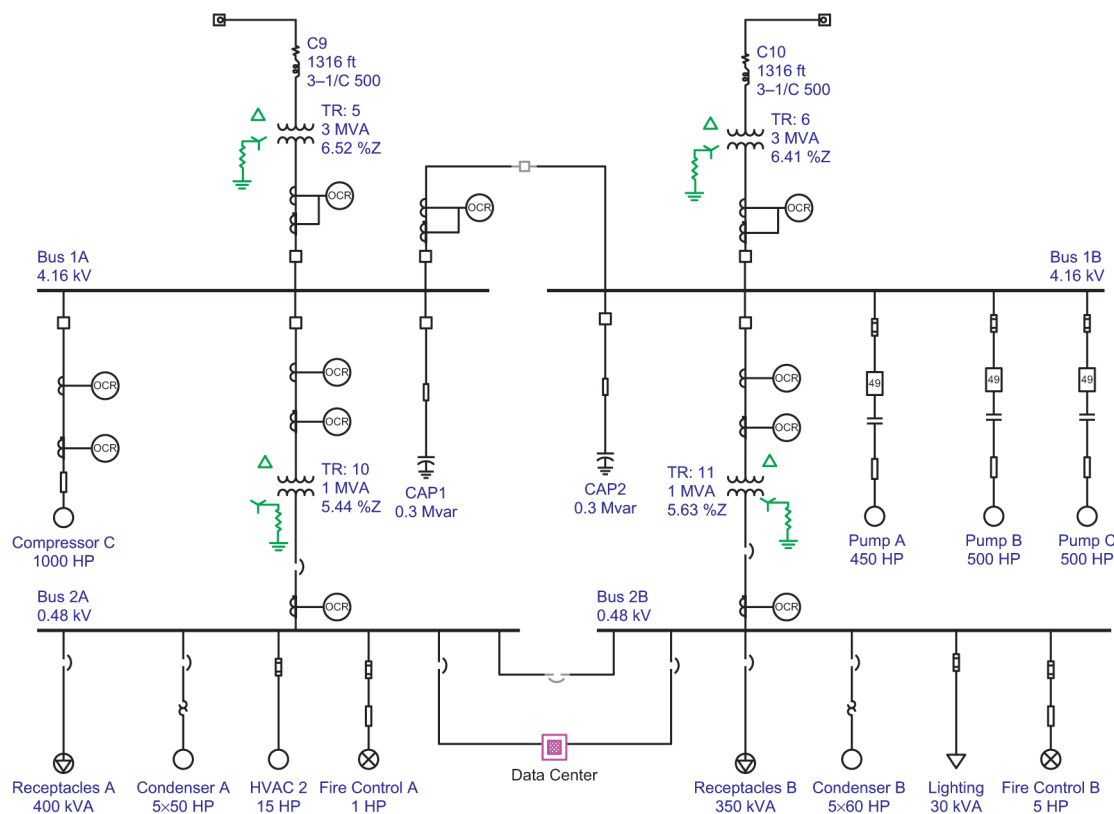


Figure 6—One-line diagram of “Substation1”—general industrial system

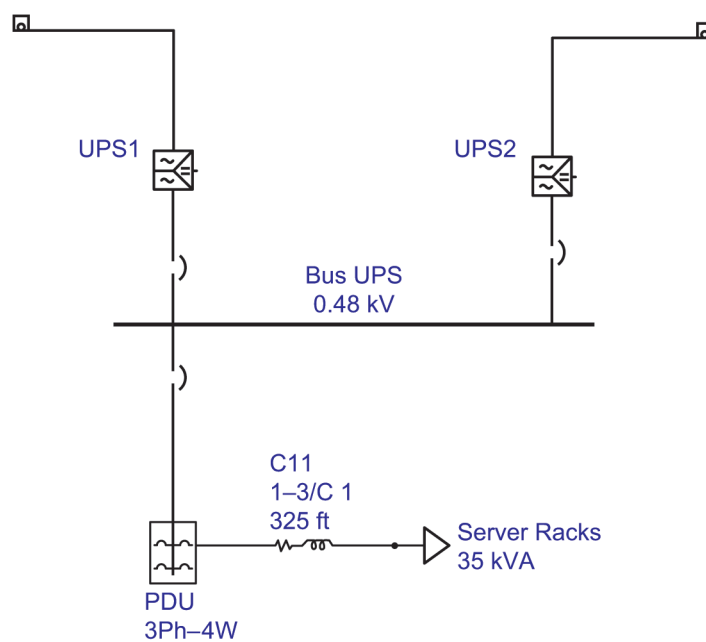


Figure 7—One-line diagram for “Data Center”

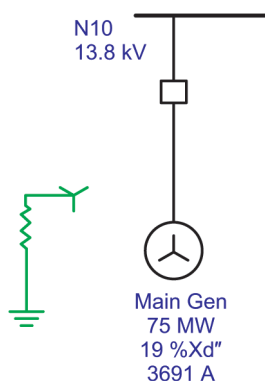


Figure 8—One-line diagram of the cogeneration station

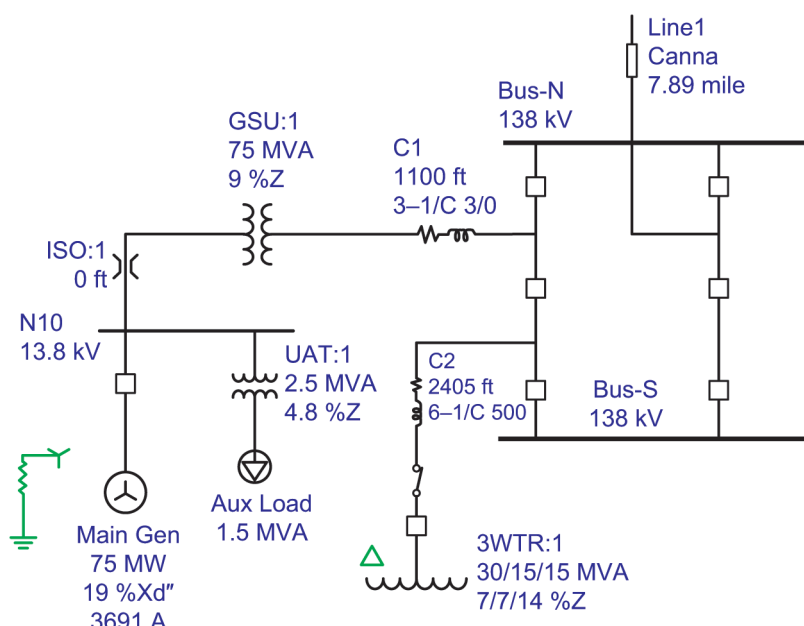


Figure 9—One-line diagram for the unit generation plant

6. Required input data

6.1 General

This clause presents input data organization in general terms along with some comments on data preparation. The data are divided into the following categories (this organization is typical of most load flow analysis software): system data, bus data, load data, source data, branch data, and transformer data.

Input data required for load flow analysis is also applicable to other analysis requiring the network model, such as short-circuit, motor starting, and stability analysis. It is therefore essential that the data preparation be performed in a consistent, thorough manner. Data values should be inputted as accurately as possible when the actual parameters are known. The input parameter uncertainty should always be conservatively taken into account. Unknown parameters should not be ignored. Instead, they should be entered using conservative assumptions based on sound engineering judgement. Impedance tolerance values, wherever applicable,

shall be considered for the calculations. Most computer programs have component libraries which contain manufacturer-specific data or typical data (i.e., NEC based cable impedances, typical transformer impedance values, etc.). The use of such libraries for selecting unknown input parameters is encouraged, but care should be taken to understand the source of the data and its applicability for the type of system.

The data shown on the one-lines described in 5.2 is an example of basic input data requirements for load flow. The system configuration, location, size of loads, generation, and equipment are often presented in graphical one-line form. Older software programs often did not have one-line diagram graphical data representation. Their input data would be organized into lists of data, which defined not only the component type, but how each element was interconnected. One-line diagram data display capability is an expected feature of software programs, which helps to reduce error in connectivity.

The process of organizing and presenting input data is not the only challenge. Not too long ago, study engineers faced the problem of system size (often measured by the number of buses present in the system). The main limiter was computer memory allocation, which limited the number of buses or node points that could be represented in a load flow model solution. The limitation in the number of buses or nodal connections required the use of network simplification methods. Some of the methods used were to reduce series-connected elements into a single-element equivalents, and to represent parts of the system as “lumped” loads (i.e., representing low-voltage loads as a single grouped load). Elements which are judged to be irrelevant to the problem being solved could be ignored to simplify the system. Modern simulation software utilizes technological advancements in computer hardware and rarely requires modeling size limitations, thus network models can be as accurate as needed. The network model complexity is now determined exclusively based on the load-flow study requirements.

6.2 System data

Most load flow programs perform their calculations using a per unit representation of the system rather than working with actual volts, amperes, and ohms. The input data to the program can be in per unit (percent) or in actual units, depending on the design of the program. Converting the system data to per unit representation requires the selection of a base MVA and base voltage. Selecting the base MVA and base voltage specifies the base impedance and base current. Computer programs automatically determine the other base voltage based on transformer turn ratios and tap settings in the system.

The system data specifies the base MVA (or kVA) for the entire system. A base of 100 MVA is typical in industrial load-flow studies, but other base values such as 10 MVA have been used.

The base kV is chosen for each voltage level. Selecting the nominal voltage to be the base voltage simplifies the analyses and reduces the chance of errors in the interpretation of results.

6.3 Bus data

Buses represent the nodes of the electrical system and can be classified based on their conditions of load and/or generation. The bus data describe each bus and the load and shunts connected to that bus. The data include the following:

- Bus ID, name, and/or number
- Bus classification (swing/voltage controlled/load bus)
- Bus service (in/out) status
- Bus nominal voltage
- Bus rating/continuous amps
- Initial voltage and angle (to be discussed later)

A more detailed explanation of the meaning of the classification terms *swing* and *voltage controlled* is presented in 7.8. These classifications were previously used by software programs to organize the buses based on classical load flow solution requirements. The use of these terms is being abandoned in favor of the concept of machine controls with modes of operation as described in 6.5 and 7.8. In fact, the requirement to have a “swing” bus (swing source) may no longer exist in some software programs for establishing load flow solutions.

6.4 Load types and data

In a load flow simulation, the voltage magnitudes and phase angles of load terminals are calculated and they change according to overall loading and network conditions. The load characteristics will also change according to the terminal voltage and phase angle changes.

The term *load bus* should not be taken literally, because the term describes only the bus electrical behaviors, without necessarily implying the presence of different equipment.

A load bus need not have load, it may simply be an interconnection point for two or more lines; in this case, Kirchhoff’s law requires that the sum of the real and reactive flows into the bus equal the sum of the flows out of the bus.

For simulation purposes, loads are most often defined as the following types:

- Constant kVA load: such as running motors where a “constant kVA” characteristic means that the complex power $S = P + jQ$ will be held constant.
- Constant impedance load: typically used for a motor which is starting, or for many static (non-motor) loads.
- Constant power and constant current loads: some load flow programs offer options for other forms of load modeling. For example, some kinds of static power conversion equipment might better be modeled as having constant real power and/or constant current characteristics.
- Generic load: used as general complex loads where the real and reactive powers (P and Q) are complex functions of terminal voltage and frequency.

In the load flow program, loads must be entered in a manner that is consistent with the design of the program. The most common scenario is for loads to be MW and Mvar at nominal voltage. This load is treated as a constant MVA, that is, independent of voltage. In some cases, a constant current or constant impedance component of load could also be entered so that the load is a function of voltage, as explained in IEEE Std 399™-1997 (4.9). Shunt capacitors generally are entered in Mvar at nominal voltage. Care must be taken to ensure that the proper sign convention is used to differentiate between capacitive and reactive loads. Most software tools account for this when loads are entered.

The load data are used to represent the load at various locations. Depending on the design of the software, load type and data may include some or all of the following:

- Load identification (either descriptive text or a unique load number)
- Load service (in/out)
- Operating state (continuous, intermittent, or spare)
- Real/reactive power rating
- Rated power factor and efficiency
- Loading in percent of rated power for different operating conditions

- Load demand factor
- Static loads (constant Z)
- Electronic loads (constant I)
- Lumped loads (constant kVA, constant Z, and/or constant I)

Motor loads (constant kVA), the efficiency and power factor of the machine at 100%, 75%, and 50% loading, as well as the no-load and overloading conditions are used to calculate the operating load. Load flow data for motors may apply to other studies such as short-circuit, motor acceleration, etc. Because of this, most software programs allow the input of motor load entered as mechanical load curves. Motor loading can be derived by using these load current curves as well.

6.5 Source data

6.5.1 Generator data

Generator data is entered for each generator in the system including any generator that may be connected to the designated system swing bus. The data defines the generator power output and how voltage is controlled by the generator. Depending on the design of the software, generator data may include some or all of the following:

- Generator identification (ID)
- Generator nameplate ratings (rated MW, MVA, power factor, and efficiency)
- Generator operating mode (swing, voltage control, Mvar control, power factor control)
- Scheduled voltage magnitude and angle (swing)
- Scheduled voltage magnitude (voltage control)
- Scheduled real power output in MW (voltage control, Mvar control, power factor control)
- Scheduled reactive power output in Mvar (Mvar control)
- Scheduled power factor in percent (power factor control)
- Maximum reactive power output in Mvar, i.e., machine maximum reactive power limit, Q_{max}
- Minimum reactive power input in Mvar, i.e., machine minimum reactive power limit, Q_{min}
- Generator service (in/out) or state

Other items that might be included in the model data are the generator MVA base and the generator's internal impedance for use in short-circuit and dynamic studies. Computer programs may allow a generator to regulate a remote bus voltage, although in most programs the control bus is usually the generator terminal bus/node.

6.5.2 Swing (slack) source (generator, utility connection, inverter)

The *swing* or *slack* source is a special type of source that is needed by the load flow solution process. Load flow models require at least one swing source in every isolated subsystem. In systems with strong grid interconnections, the grid connection is typically specified as the swing source. In the absence of a grid connection, the largest generator can be selected as the swing source. Note that some modern inverters can operate in swing mode without requiring the subsystem to be connected to a swing utility or generator.

A generation designated as the swing source(s) needs to provide the balance of power to the system; i.e., power absorbed by loads, power losses, and the power delivered by non-swing source(s). The swing generator adjusts its governor (in isochronous mode) to supply MW and its excitation voltage to supply Mvar needed to balance the power flow in each subsystem.

The swing source is also referred to as the *infinite* source. In reality, the power that a swing source can release is finite, but can be larger with respect to the other generators in the system. During the operation, the terminal voltage of this generator is specified to remain constant in magnitude V and phase angle θ , whereas, active and reactive powers will change according to the network demand. For this reason, this source is also called the θ , V source.

When a utility connection is modeled, it is a Thevenin equivalent of the supply system upstream of the facility, modeled as a driving voltage in series with an impedance. The internal driving voltage may be set as the swing source. The internal impedance is used to determine the bolted short-circuit current available from the supply network at the point of connection. The user is cautioned that when multiple connections from different parts of an interconnected utility grid are made to one interconnected industrial complex, substantial errors may result if network diakoptics are not considered (Happ [B3]).

6.5.3 Voltage control generator

During load flow simulations, the voltage magnitude at the generator terminal (or a remote bus) is kept constant, and the reactive loading of the machine is adjusted within its reactive power (Q_{\min} and Q_{\max}) limits to satisfy system Mvar demand while maintaining the scheduled voltage. The active power supplied is kept constant at its scheduled value, i.e., the generator is base loaded (the governor is in droop mode). This represents a generator where the voltage is controlled by the excitation system and the real power is controlled by the prime mover. For this reasons, the generator is also defined as the P - V source, where the quantities θ and Q vary according to the network demand.

If a source does not regulate its output voltage, the real power P and the reactive power Q are fixed in magnitude; thus, as load varies, the voltage magnitude V and the voltage θ angle vary. Examples of P - Q sources are those configured as Mvar and power factor control.

6.6 Branch data

Data are also entered for each branch in the system. Herein the term *branch* refers to all elements that connect two buses including transmission lines, cables, series reactors, series capacitors, and transformers. In the real system, there may be multiple elements in series (e.g., an overhead transmission circuit that transitions into a cable circuit); when using modern simulation software that does not impose practical limits on the number of nodes in the model, it is preferable to treat each of these elements separately connected by a “node.” The data items include the following:

- From bus/to bus identifications
- Branch identification (especially if there are parallel branches connecting the specified from and to buses)
- Branch service (in/out) or state
- Physical length (cable and transmission line)
- Resistance in Ohms or Ohms per unit of length
- Resistance in Ohms or percent on the chosen study base MVA
- Reactance in Ohms or Ohms per unit length
- Reactance in Ohms or percent on the chosen study base MVA base
- Charging susceptance (shunt capacitance)
- Line continuous amperage rating

In industrial systems, overhead transmission lines and cable circuits are typically short, so the charging capacitance of these circuits is often not relevant to a load flow solution (although it is important in some other industrial system calculations). Hence, charging susceptance is often omitted from industrial system load flow models. When susceptance is included, lines are often represented by a model with series resistance and reactance and one-half of the charging susceptance placed on each end of the line. The resistance, reactance, and susceptance are usually input in either per unit or percent, depending on program design.

Line ratings are normally input in amperes or MVA, depending on the design of the software. Current ratings can be converted to MVA with the formula:

$$\text{Rated MVA} = \frac{\sqrt{3} \times \text{kV}_{\text{Base}} \times \text{Rated A}}{1000} \quad (1)$$

A series reactor, series capacitor, or transformer would not usually have a charging susceptance term.

6.7 Transformer data

Additional data are required for transformers. These can either be entered as part of the branch data or as a separate data category, depending on the particular load flow program being used. Depending on the design of the software, these additional data may include the following:

- Transformer service (in/out) or state
- Transformer identification
- Rated MVA of the transformer based on transformer cooling class and number of cooling stages
- Transformer impedance (Z) in percent on stated MVA base. Some software may allow specifying positive and negative manufacturing tolerance values for transformer impedance.
- Three-winding transformer impedance in percent on primary MVA base. Use caution to take the time to understand how the design of the software expects these impedances to be stated. The impedances of three-winding transformers can be stated either as determined by factory tests as separate primary-secondary, primary-tertiary, tertiary-secondary values on a stated base, or equivalent values to a fictitious center node, also on a specified base.
- Fixed tap setting in percent or kV, as required by the design of the software
- Phase shift angle in degrees, if applicable
- Tap step size for automatic on-load tap changers
- Maximum tap position for fixed and/or automatic on-load tap changers
- Minimum tap position for fixed and/or automatic on-load tap changers

The organization of transformer tap data requires an understanding of the tap convention used by the load flow program to ensure the representation gives the correct boost or buck in voltage. Transformers with rated primary or secondary voltages that do not match the system nominal (base kV) voltages on the terminal buses will require an off-nominal tap representation in the load flow model (and possibly require corresponding adjustment of the transformer impedance).

6.8 Example system input data

Input data for the example system described in 5.2 and used for the load flow analysis example in Clause 9 is documented in tables provided in Annex B. The input data listed in those tables is not limited to, or may not follow, the generic format of input data described in 6.1 through 6.7. The input data format can be different for

different software simulation tools. The format of the computer simulation tool used to perform the load-flow study described in [Clause 9](#) was used to populate the data tables of [Annex B](#).

Note that the amount of input parameters required depends on the complexity and capability of the simulation tool used to perform a load flow analysis and the needs of the analysis. As always, the power system model needs to be as simple or as complex as is needed to solve the problem at hand. For simplicity, the tables in [Annex B](#) only contain the basic information which is considered common to most software analysis tools. Additional input parameters may be required to apply some of the analysis methods described in [Clause 7](#). However, these additional parameters were omitted for simplicity purposes.

7. Methodology and standards

7.1 General

Because load flow calculations involve solutions of a set of non-linear equations, manual solutions are impractical except for purely pedantic examples. Before digital computer solutions were available, load flow simulations were conducted using analog boards. In the very early days, these analog boards were simple dc devices with the elements of the power system represented by resistances. Obviously, the answers were not absolutely accurate, but amazingly they were close enough for practical application.

Special purpose analog boards called *ac network analyzers* were developed in the late 1920s. Power system networks under study were represented by an equivalent, scaled-down network. The devices allowed the analysis of a variety of operating conditions and expansion plans. The simulation setup time was long, and the time to conduct studies and record the results slowly made the network analyzers become cost ineffective. Furthermore, the large amount of hardware required led to their diminishing use. Only a few network analyzers were operational by the mid-1950s.

Computers began to emerge in the late 1940s as computational tools. By the mid-1950s, large-scale computers of sufficient speed and size to handle the requirements of a power system network calculation were available. Parallel to the hardware development, algorithms to efficiently solve the network equations were developed. Ward and Hale developed a successful load flow program using a modified Newton iterative procedure in 1956 (Ward and Hale [B9]). The application of the Gauss-Seidel iteration algorithm followed soon after. Research in algorithms continued and the Newton-Raphson method was introduced in the early 1960s (Tinney and Hart [B8]). Considerable research has been performed in the interim years to improve the performance of these algorithms, making them more robust and able to handle additional power system components; the new algorithms accommodate much larger network sizes. These calculation algorithms persist today and include adaptive methods which can adjust to higher system convergence demands.

7.2 Overall solution

A rough outline of solution of the power flow problem is the following:

- a) Make an initial guess of all unknown voltage magnitudes and angles. It is common to use a “flat start” in which all voltage angles are set to zero and all voltage magnitudes are set to 100% (or 1.0 per unit).
- b) Set an initial angle for the swing bus. The angle assigned to the swing bus is the reference for the bus voltage angles calculated for each bus in the system. Some engineers arbitrarily use 0° as the swing bus angle, but this typically results in negative signs on load bus voltage angles. A tradition going back to the days of ac network analyzers is to use an angle such as 50° for the swing bus to avoid negative bus voltage angles in the final solution.
- c) Solve the power balance equations using the most recent voltage magnitude and angle values.
- d) Solve for the change in voltage angle and magnitude.

- e) Update the voltage magnitude and angles.
- f) If the solution is adequate as defined by a set of “stopping conditions,” terminate the simulation and report the results. If the solution is not adequate, return to step c) to calculate a new solution.

7.3 Problem formulation

The load flow calculation is a network solution problem. As explained in previous subclauses, and summarized in Table 1, for any power system:

The variables given (i.e., the knowns) are:

- Voltage V and phase θ at the swing bus
- Voltage V (in magnitude) and active power P , for P - V buses
- Active power P and reactive power Q for the P - Q buses

The variables found (i.e., the unknowns) are:

- Voltage angle θ and reactive power Q at the P - V buses
- Voltage angle θ and voltage magnitude V for the P - Q buses

Table 1—Knowns and unknowns in power systems^a

Type of element	Variables given (knowns)	Variables found (unknowns)
Generator	Real power (P)	Voltage angle (θ)
	Voltage magnitude (V)	Reactive power (Q)
Load or generator	Real power (P)	Voltage angle (θ)
	Reactive power (Q)	Voltage magnitude (V)
Slack	Voltage angle (θ)	Real power (P)
	Voltage magnitude (V)	Reactive power (Q)

^aHere slack bus refers to swing bus as defined in this context.

The determination of the above unknown quantities is possible by writing a system of equations, one equation for each of the above nodes, and then using a numerical method to solve those equations. Note that in theory, there does not have to be a solution to a set of non-linear equations. However, if the equations are properly written, the fact that they represent a practical power system means that there will be a solution. On the other hand, there are some special cases where the set of non-linear equations for a power system may have multiple solutions. Those cases form a special category of problems designated as *voltage stability* that is beyond the scope of this document (see Kundur [B5] for information on voltage stability).

For modeling purposes, we can represent branches of networks by their branch admittance; therefore, all the voltages and currents in the network are related by the following matrix equation:

$$[I] = [Y][V] \quad (2)$$

where

$[I]$ is the matrix of total positive sequence currents flowing into the network nodes (buses)

$[V]$ is the matrix of positive sequence voltages at the network nodes (buses)

$[Y]$ is the nodal admittance matrix

Equation (2) is a linear algebraic equation with complex coefficients. If either $[I]$ or $[V]$ is known, the solution for the unknown quantities could be obtained by application of various solution techniques for linear equations.

Because of the physical characteristics of generation and load, the terminal conditions at each bus (or node), are normally described in terms of active and reactive power (P and Q).

The bus current at bus i is related to these quantities as follows:

$$I_i = \frac{(P_i + jQ_i)^*}{V_i^*} \quad (3)$$

Where * designates the conjugate of a complex quantity. Combining Equation (2) and Equation (3) yields Equation (4):

$$\left[\frac{P - jQ}{V^*} \right] = [Y][V] \quad (4)$$

Equation (4) constitutes a non-linear system of equations, generally of large dimensions which cannot be readily solved by closed-form matrix techniques. Because of this situation, load flow solutions are obtained by procedures involving numerical techniques based on iterative solution algorithms.

7.4 Iterative solution algorithms

Since the original technical papers describing digital load flow solution algorithms appeared in the mid-1950s, a seemingly endless collection of iterative schemes has been developed and reported. Many of these are variations of one or the other of two basic techniques that are in widespread use by the industry today: the Gauss-Seidel technique and the Newton-Raphson technique. The preferred techniques used by most commercial load flow software are variations of the Newton technique.

All of these techniques solve bus equations in admittance form, as described in 7.3. This system of equations has gained widespread application because of the simplicity of data preparation and the ease with which the bus admittance matrix can be formed and changed in subsequent cases.

In a load-flow study, the primary parameters are as follows:

- P is the active power into or out of the network
- Q is the reactive power into or out of the network
- $|V|$ is the magnitude of bus voltage
- θ is the angle of bus voltage referred to a common reference (the swing bus)

In order to define the load flow problem, it is necessary to specify two of the four quantities at each bus. For generating units, it is reasonable to specify P and $|V|$ because these quantities are controllable through governor and excitation controls, respectively. For loads, one generally specifies the real power demand P and the reactive power Q . Since there are losses in the transmission system and these losses are not known before the load flow solution is obtained, it is necessary to retain one bus where P is not specified. At this bus, called a swing bus, $|V|$ as well as θ , the swing-bus angle, are specified. Since θ is specified (that is, held constant during the load flow solution), it is the reference angle for the system. The swing bus is therefore also called the *reference bus*. Since the real power, P , and reactive power, Q , are not specified at the swing bus, these quantities are free to adjust to compensate transmission losses in the system.

Table 2 summarizes the standard electrical specifications for the three bus types. The classifications *generator bus* and *load bus* should not be taken as absolute. There will, for example, be occasions where a pure load bus may be specified by P and $|V|$.

With most software, the generator specification of holding the bus voltage constant and calculating the reactive power output will be overridden in the load flow solution if the generator reactive output reaches its maximum or minimum var limit. In this case, the generator reactive power will be held at the respective limit, and the bus voltage will be allowed to vary.

7.5 Gauss-Seidel iterative technique

Descriptions of load flow solution techniques can become rather complicated, due more to the notation required for complex mathematics rather than the basic concepts of the solution method. In the following subclauses, therefore, the basic techniques are developed by considering their application to a dc circuit. Applications to ac problems are then a natural extension of the dc problem.

Table 2—Load flow bus and source specifications

Bus/source type	P	Q	$ V $	θ	Comments
Load	✓	✓			Usual load representation
Synchronous generator	✓	$Q^- < Q_g < Q^+$	✓		$ V $ is held as long as Q_g is within limits Q^- = minimum var limit Q^+ = maximum var limit
Synchronous condenser	✓	$Q^- < Q_g < Q^+$	✓		$P = 0$ (very small) $ V $ is held as long as Q_g is within limits
Swing			✓	✓	Swing bus must adjust net power to hold voltage constant (essential for solution)

The Gauss-Seidel solution algorithm is the easiest limit to understand. The performance of the Gauss-Seidel technique will be illustrated using the direct current circuit shown in Figure 10.

Bus 3 is a load bus with specified per unit power. Bus 2 is a generator bus (connected to a generator) with power specified, and Bus 1 is the swing bus (connected to a swing generator) with voltage specified. The voltages V_2 and V_3 are sought. From these, the branch flows can be calculated.

The system equations on an admittance basis are from Equation (2).

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (5)$$

The process of creating the admittance matrix is embedded deeply within load flow software, so it is not something that the study engineer would ever have to do manually. But it is still helpful to understand the general principles involved in that process (Stagg and El-Abiad [B6], Stevenson [B7], Tinney and Hart [B8]). The basic rules for construction of the Y matrix are:

- The diagonal terms in the Y matrix are the sum of the admittances of the lines leaving a bus, plus the admittance of any shunt elements connected to the bus, plus one-half of the charging admittance defined for each connected line. This means that the admittance matrix will always be a square matrix in which the number of diagonal elements equals the number of buses in the system model.

- b) The off-diagonal terms Y_{ij} are the negative of the line admittances between buses i and buses j , where a connection between bus i and bus j is present. If there is no connection between bus i and bus j , the ij term is zero.

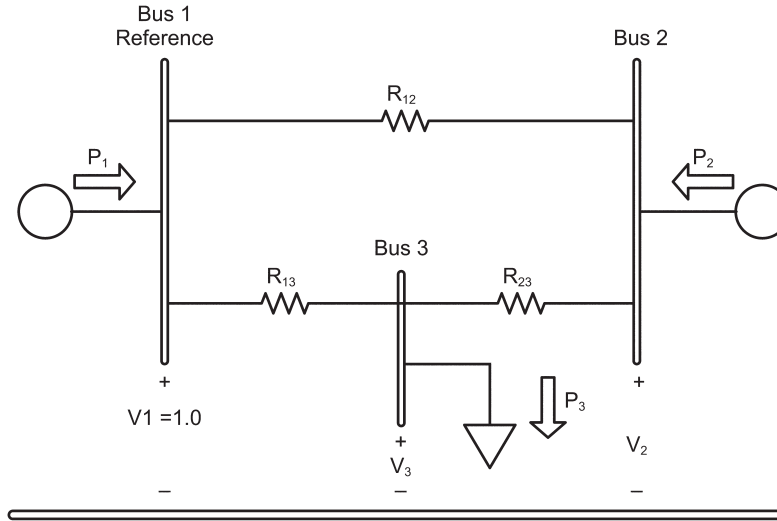


Figure 10—Three-bus dc network

$$Y_{ij} = \frac{-1}{Z_{ij}} \quad (6)$$

Because there generally will not be an actual network connection between every possible pair of nodes in the system, the Y matrix tends to be very sparse (i.e., most of the off-diagonal terms are zero).

From Equation (5),

$$I_2 = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 \quad (7)$$

or

$$V_2 = \frac{1}{Y_{22}} [I_2 - (Y_{21}V_1 + Y_{23}V_3)] \quad (8)$$

substituting

$$I_2 = \frac{P_2}{V_2} \quad (9)$$

$$V_2 = \frac{1}{Y_{22}} \left[\frac{P_2}{V_2} - (Y_{21}V_1 + Y_{23}V_3) \right] \quad (10)$$

this is a nonlinear equation in V_2 .

For Bus 3, a similar procedure yields

$$V_3 = \frac{1}{Y_{33}} \left[\frac{-P_3}{V_3} - (Y_{31}V_1 + Y_{32}V_2) \right] \quad (11)$$

where the negative sign on P_3 is from the load sign convention.

Equation (10) and Equation (11) are in a form convenient for the application of the Gauss-Seidel iterative solution technique. The steps in this procedure are as follows:

- Step 1: Assign an estimate of V_2 and V_3 (for example, $V_2 = V_3 = 100\%$). Note that V_1 is fixed.
- Step 2: Compute a new value for V_2 using the initial estimates for V_2 and V_3 [see Equation (10)].
- Step 3: Compute a new value for V_3 using the initial estimate for V_3 and the just computed value for V_2 [see Equation (11)].
- Step 4: Repeat Step 2 and Step 3 using the latest computed voltages V_2 and V_3 until the solution is reached. One complete computation of V_2 and V_3 is one iteration.

The computed voltages are said to *converge* when, after each iteration, the voltages come closer and closer to the actual solution. Since the computation time increases linearly with the number of iterations, it is necessary to have the computer program check the precision of the solution after each iteration, and decide whether the difference between the last computed voltages and the previous values are less than the precision for each bus in the system, or whether further computations are required.

The criterion specifying the desired accuracy is called the *convergence criterion*. The number of iterations may be entered or changed in most load flow programs. For the Gauss-Seidel method, the user can also change a solution acceleration factor; slowing the factor in case of convergence problem and increasing the factor for large network solutions. The typical range for the acceleration factor is 1.2 to 1.7.

There are various ways to define when a solution has converged. One reliable convergence criterion is the power mismatch check, in which the software determines the sum of the calculated power flows (real and reactive) on all branches connected to each bus compared with the user-specified bus real and reactive power. The difference, which is the power mismatch, is a measure of how close the computed voltages are to an ideal, or exact, solution. The power mismatch tolerance is generally specified in the range of 0.01 to 0.0001 per unit on the system MVA base. The total power mismatch is also printed in the output report of load flow programs and is an indication of how valid is the load flow solution. Ideally the power mismatch of the entire network should be $0 + j0$. Power mismatch reporting should be done and reported at a bus level as well, so that the user can understand which buses have power mismatch greater than the specified mismatch tolerance and therefore represent the points that are confounding the iterative solution. With the source of the convergence problem identified, model adjustments can be made to aid the load flow to reach a solution and/or reduce the iteration time.

Another common convergence check evaluates the maximum change in any bus voltage from one iteration to the next. A solution with desired accuracy is assumed when the change is less than a specified small value, for example, 0.000 001 per unit.

Some of the things that can lead to convergence difficulties include:

- Errors in the input data
- System is too weak to carry the load
- Insufficient var in the system to support the voltages

- Significant disparity in the magnitudes of branch impedances that terminate at the same bus

A voltage check is dependent on the rate of convergence and is thus less reliable than the power mismatch check. However, the voltage check is much faster (computationally, on a digital computer) than the power mismatch check, and since the power mismatch will be large until the voltage change is quite small, one may economically use a procedure where computation of mismatch is avoided until a small amount of voltage change occurs.

Solution of an ac network would be similar to the solution of a dc network except that both resistive and reactive impedances must be recognized, and the solution must calculate both voltages and angles. For the three-bus example, voltage magnitude and angle at Bus 1, generator power and bus voltage at Bus 2, and real and reactive load power at Bus 3 would be specified. The load flow solution would determine the voltage angle and generator reactive power output of Bus 2 and the voltage magnitude and angle at Bus 3.

The ac version of Equation (9) and Equation (10) can be obtained from Equation (4) as follows:

$$V_i^{(m)} = \frac{1}{Y_{ii}} \left(\frac{P_i - jQ_i}{V_i^{*(m-1)}} - \sum_{k=1}^{i-1} Y_{ik} V_k^{(m)} - \sum_{k=i+1}^N Y_{ik} V_k^{(m-1)} \right) \quad i = 1, 2, \dots, N-1 \quad (12)$$

where

- N is the number of buses in the system, and the swing bus is bus N
- m is the present iteration number
- i, k are bus indices
- V, Y are complex voltage and admittance, respectively
- V^* is the complex conjugate of V

7.6 Newton-Raphson iterative technique

The Gauss-Seidel technique is inefficient, often requiring hundreds of iterations to achieve an acceptable solution. And it can fail to converge in some specialized instances. Problems that cannot be solved using the Gauss-Seidel technique may often be solved using the Newton-Raphson technique.

This approach uses the partial derivatives of the load flow relationships to estimate the changes in the independent variables required to find the solution. In general, the Newton-Raphson technique achieves convergence using fewer iterations than the Gauss-Seidel technique. However, the computational effort per iteration is somewhat greater.

To apply the Newton-Raphson technique to the three-bus example in Figure 10, the bus powers are expressed as nonlinear functions of the bus voltage.

$$\begin{aligned} P_1 &= V_1 (Y_{11} V_1 + Y_{12} V_2 + Y_{13} V_3) \\ P_2 &= V_2 (Y_{21} V_1 + Y_{22} V_2 + Y_{23} V_3) \\ P_3 &= V_3 (Y_{31} V_1 + Y_{32} V_2 + Y_{33} V_3) \end{aligned} \quad (13)$$

Small changes in bus voltages (ΔV) will cause corresponding small changes in bus powers (ΔP). A linearized approximation to the power change as a function of voltage changes can be obtained as follows:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial V_1} & \frac{\partial P_1}{\partial V_2} & \frac{\partial P_1}{\partial V_3} \\ \frac{\partial P_2}{\partial V_1} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} \\ \frac{\partial P_3}{\partial V_1} & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix} \quad (14)$$

or symbolically:

$$[\Delta P] = [J][\Delta V]$$

where $[J]$, the Jacobian matrix, contains the partial derivatives of power with respect to voltages for a particular set of voltages, V_1 , V_2 , and V_3 , that is, the partial derivations of Equation (13). When one or more of the voltages changes substantially, a new Jacobian matrix must be computed.

In the load flow problem, V_1 is specified; that is, $\Delta V_1 = 0$. Also, since ΔP_1 does not enter the computations explicitly, Equation (14) may be reduced to

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} \\ \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} \end{bmatrix} \begin{bmatrix} \Delta V_2 \\ \Delta V_3 \end{bmatrix} \quad (15)$$

Changes in V_2 and V_3 due to changes in P_2 and P_3 are obtained by inverting $[J]$ to obtain

$$[\Delta V] = [J]^{-1}[\Delta P] \quad (16)$$

The Newton-Raphson load flow solution method is then as follows:

- Step 1: Assign estimates of V_2 and V_3 (for example, $V_2 = V_3 = 1.0$).
- Step 2: Compute P_2 and P_3 from Equation (13).
- Step 3: Compute the differences (ΔP) between computed and specified powers:

$$\Delta P_2 = P_2 - P'_2 \quad (17)$$

$$\Delta P_3 = P_3 - P'_3$$

Where the prime indicates specified value.

- a) Step 4: because the condition $\Delta P \neq 0$ is caused by errors in the voltages, the voltages should be incorrect by an amount that is closely approximated by ΔV as evaluated from Equation (16).

Therefore, the new estimate for the bus voltages is

$$\begin{bmatrix} V_2 \\ V_3 \end{bmatrix}_{new} = \begin{bmatrix} V_2 \\ V_3 \end{bmatrix}_{old} - [J]^{-1} \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \end{bmatrix} \quad (18)$$

This is the basic equation in the Newton-Raphson method. The negative sign is because of the way ΔP was defined.

- b) Step 5: Re-compute and “invert” the Jacobian matrix using the last computed voltages and compute the new estimate for the voltages using Equation (17) and Equation (18). Repeat this procedure until ΔP_2 and ΔP_3 are less than a small value (convergence criterion).

The convergence of the Newton-Raphson technique is not asymptotic as was the case with the Gauss-Seidel iterative scheme. The convergence is very rapid for the first few iterations and slows as the solution is neared.

For the ac load flow solution, the Jacobian matrix may be arranged as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} \quad (19)$$

Where the complex bus voltage is written in polar coordinates, $|V| \angle \theta$. The Jacobian matrix can be arranged in many different ways to fit the particular programming techniques selected. An approximation to the Newton-Raphson formulation can be obtained by observing that, for a small change in the magnitude of bus voltage $\Delta |V|$, the real power, P , does not change appreciably. Similarly, for a small change in bus voltage phase angle $\Delta \theta$, the reactive power, Q , does not change very much.

Thus, in Equation (19):

$$[J_2] = \left[\frac{\partial P}{\partial |V|} \right] \cong 0 \quad (20)$$

$$[J_3] = \left[\frac{\partial P}{\partial \theta} \right] \cong 0 \quad (21)$$

This allows Equation (19) to be “decoupled” into the following form:

$$[\Delta P] = [J_1][\Delta \theta] \quad (22)$$

$$[\Delta Q] = [J_4][\Delta |V|] \quad (23)$$

Note that these two equations can be solved independently and sequentially, thereby reducing the storage and solution time requirements compared to using the full Jacobian. The decoupled Newton-Raphson technique may be used in applications where computational speed is important and the starting solution is close to the actual solution. This situation often occurs where a series of contingencies are being investigated about a previously solved reference case. However, the decoupled technique does not work well for systems with large branch resistance to reactance ratios, such as often found in industrial systems.

7.7 Comparison of load flow solution techniques

The two techniques described in the previous subclauses are the basic load flow solution techniques. There are many variations and improvements to these techniques that have been developed and incorporated into load flow programs to improve the starting or convergence characteristics.

Although it is useful to understand how load flow solution techniques work, it is more important to understand the characteristics that these techniques exhibit. Because their convergence characteristics depend on network, load, and generator conditions, each of the iterative techniques discussed has its own strengths and weaknesses.

Gauss-Seidel methods generally exhibit poor convergence characteristics when compared to Newton methods and thus are not used as often for practical power flow solutions. Most of the recent research into load flow solution techniques has centered on Newton methods. Variations of the Newton methods have been developed to overcome the weaknesses of the original methods, especially the ability to converge from a poor initial voltage estimate. That said, some modern software offers Gauss-Seidel, Fast-Decoupled, Newton-Raphson, and Adaptive Newton-Raphson solutions. In some cases, the study engineer must choose the method to be applied. Some software provides tools to update the initial set of bus voltages and angles with the results of the last successful load flow run. The updated initial values can then be used as initial conditions for future load flow runs with the same method or as initial conditions to aid an alternative load flow method reach convergence.

The Adaptive Newton-Raphson method employed by some commercial load flow software combines good convergence characteristics and solution algorithm robustness. Details on these algorithms are available in the reference sections of the software load flow methodology user guide.

7.8 Load flow source models for active and reactive power limits and controls

Traditional load flow modeling as described in 6.3 and 7.3 require a swing source and P - V and P - Q sources to achieve a solution. The behavior of the generator controls and the limits in active and reactive power generation of most modern sources of power, are not exactly modeled by the use these “traditional” load flow solution modes. Controls and limiters reduce the amount of active and reactive power generation under steady-state as well as transient conditions. Furthermore, the application and selection of the load flow modes of operation in a simulation needs to be determined based on the mode of operation of the controllers of each of the main elements of a generator as shown in Figure 11 for each of the machines in a system (see Kundur [B5] for more details on each component).

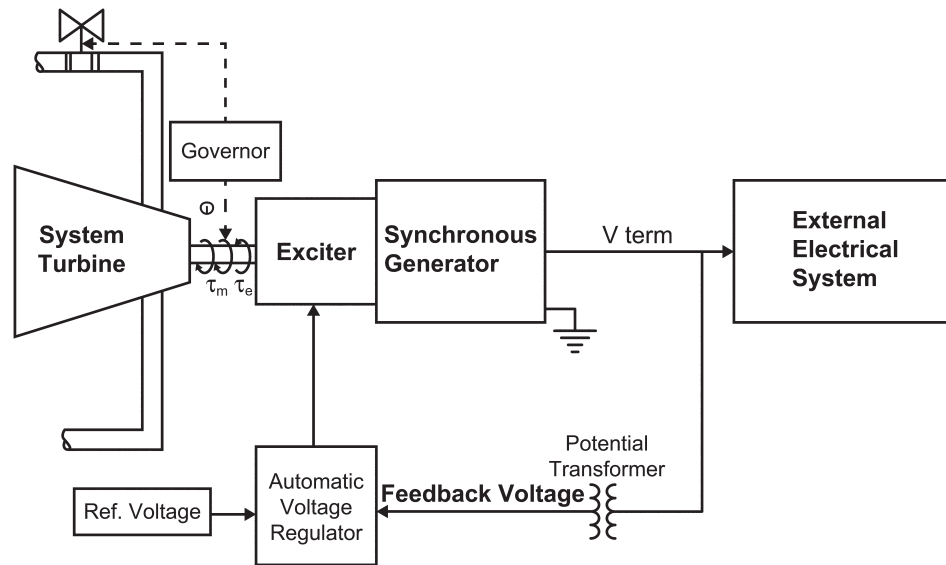


Figure 11—Synchronous generator controls

If the system voltage and frequency from the load flow solution are not within a specific range, the generators will not be able to provide the desired voltage or power output. Table 3 shows how the modes of operation are related to the actual operational mode of the generator as described in Figure 11. The table also describes the parameters that are used as set points.

Table 3—Synchronous generator operating mode for load flow (LF) studies

LF mode	Controlled parameter	Automatic voltage regulator (AVR) mode	Governor mode	Pe limit	Qe limit
Swing	V, Speed	Voltage control	Isochronous	P_{max}/P_{rated}	Qmax and Qmin
P-V	V, Pe	Voltage control	Droop	N/A	Qmax and Qmin
P-Q	Qe, Pe	Mvar control	Droop	N/A	N/A
P-Q	Qe, Pe	PF control	Droop	P_{max}/P_{rated}	N/A

Table 3 introduced several generation control elements and modes of operation. Load flow solutions are considered to be steady-state snapshots or a power system operating with different control limits. The term *isochronous* and *droop* represent the mode of operation of the governor speed and load controller. The terms *voltage control*, *Mvar control*, and *power factor control* indicate the mode of operation of the automatic voltage regulator of the excitation system. The terms *Qmax* and *Qmin* stand for over- and under-excitation Mvar limiters. The term P_{max} stands for maximum prime mover mechanical power, and the term *Pe* in this clause stands for generator electrical power output.

Synchronous generators have physical output limits. Heating effects physically limit the maximum power and current output of a generator. The prime mover has a physical limit on the amount of energy it can convert to mechanical torque. The generator capability curve shown in Figure 12 shows some of the electrical power output physical limits of a generator.

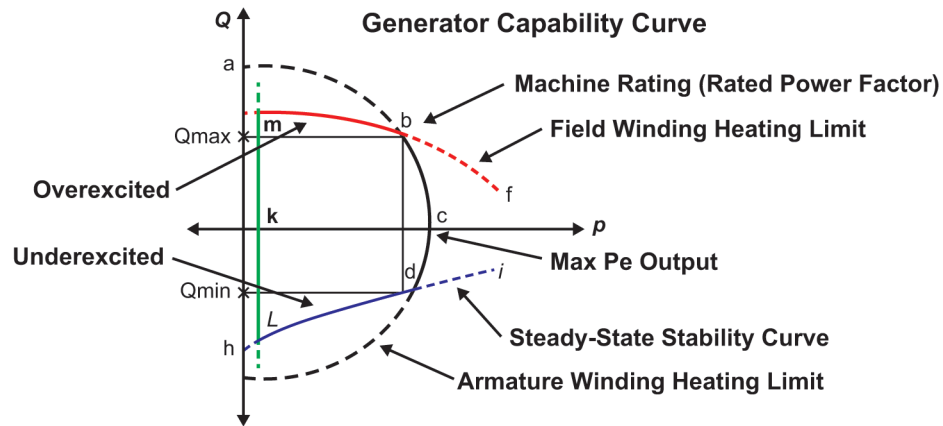


Figure 12—Synchronous generator capability curve

The main purpose of the controls and limiters is to stay within the desired operating range, i.e., the generator is underexcited (leading power factor), overexcited (lagging power factor), voltage range, etc. However, when the generator output reaches overload conditions under steady-state operation, the generators will also adjust their active and reactive power output (based on safety-margin protective limits as defined). These controls may cause a transition in the mode of operation of load flow programs based on the reactive power output characteristics.

This means that under some load flow solutions, the generator may be operating in the P-V mode, but then switch to P-Q (Mvar control mode or power factor control mode). This transition point may be critical for simulating voltage stability limits in load flow simulations.

Figure 13 shows an example of an actual generator capability curve which includes over-excitation limiter (OEL) and under-excitation limiter (UEL) curves. The arrows indicate the region boundary where the load flow simulation would switch from P-V to P-Q. The UEL and OEL would prevent the generator from overheating and reduce the reactive power output of the generator. In load flow solutions, it is critical to determine how much reactive power can be provided, and thus the load flow solution should include considerations on such limits. Note that the limits change depending on ambient temperature, and as such, a range of curves between maximum and minimum ambient temperature may be seen.

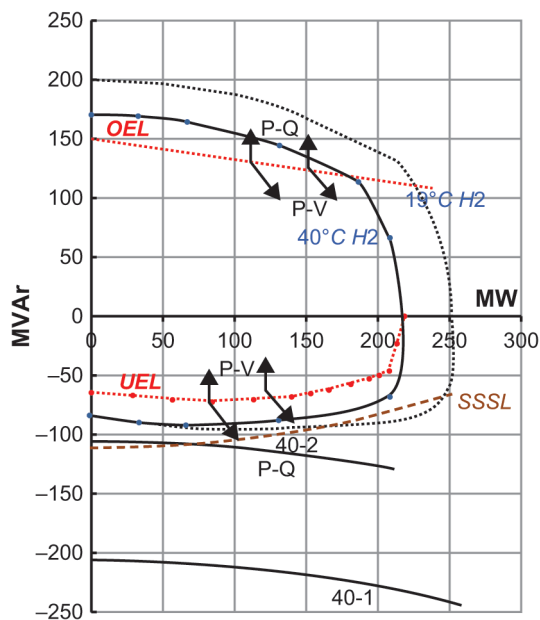


Figure 13—Generator P-V to P-Q switch region map

The OEL operation follows a thermal capability limit similar to the one shown in Figure 14. Note that for the purpose of load flow analysis (single snapshot of the system operation), it may be considered that the overload time is long and that the generator reactive power output will be limited in similar fashion as it is shown in Figure 13 (represented as a line).

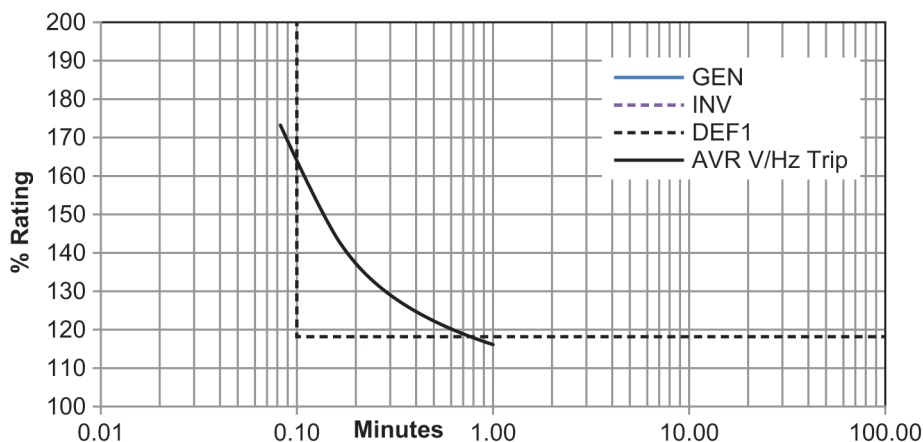


Figure 14—OEL limiter inverse time overcurrent chart

Similar to generators, other types of sources like power electronic converters (inverters) have controls which limit the active and reactive power output. The limits on the converter sources are established based on the system voltage (input terminal voltage) and active power being generated by the source. The limits on the reactive power are typically represented by two main types of curves called P-Q and Q-V curves. Figure 15 shows generic examples of what the curves may look like for different devices.

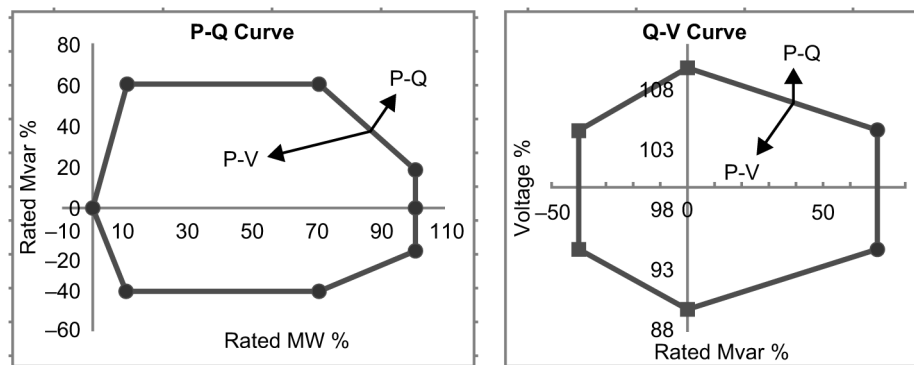


Figure 15—Converter P-Q and Q-V reactive power limits

The P-Q and Q-V curves may have different shapes and ranges of operation. The bounded area typically represents the P-V operating region of the converter. This means that the power electronics (firing angle and pulse width modulation controls) have the ability to control the output voltage at the terminal of the device within the specified region. Outside the operating region bounded by the curves, the converter source will operate as a P-Q source.

The P-Q curve plots the active power generated versus the reactive power limits of the converter. The Q-V curve shows the dependency of the source on the terminal voltage output of the converter. This means that the reactive power is limited by the generated kW and the terminal voltage.

It is important to determine the amount of reactive power available in a system. This becomes a requirement for most systems with a power converter which interconnects to a power grid (utility). Load flow simulations in power system analysis software may require several iterations to determine the reactive power capability of a photovoltaic or wind turbine converter system. The reason is that the reactive power limits apply to each individual converter. Typically a controller supervises the flow of each converter source depending on the electrical distance of the impedance elements in the collector system.

The example selected for load flow analysis contains examples of both photovoltaic and wind turbine power converters interconnected to a main industrial complex. With the advent of distributed generation and renewable energy sources, the load flow simulations need to be capable of modeling interactions within different types of voltage sources. The discussion in this clause focused on inverters' P-Q and Q-V capability curves. Other converter types acting as loads in energy conversion applications, such as rectifiers in electrolysis plants, and adjustable speed drives (ASDs or VFDs) for industrial application process control, have the capability to control the reactive power by operating in one or two quadrants. The example system also contains converter elements operating with this capability.

8. Model and data validation

Load flow models should be validated prior to issuing any recommended changes to the system. Load flow validation may be performed by acquiring actual values of electrical variables in the system, and comparing the simulation results with actual system measurements.

For existing systems, the network configuration, load, and generation are often chosen to match a known operating condition, so that results can be compared to values obtained from operating experience to help validate the model. The base case represents the system in the normal operating mode supplying normal loading conditions.

That said, the usual purpose of load flow simulation is to gain insight into the performance of a system in response to various operating contingencies, and it is possible that there will not be exact numerical correlation between simulation results and measurements taken from the actual system for all corresponding conditions.

The reason for performing load flow validation is to benchmark the power flow model with actual operating conditions under normal loading and network topology. Once a benchmark is achieved via load flow validation techniques, then any simulation performed thereafter will use more accurate loading, generation, and network topology.

There are special situations where the tolerances between acceptable and unacceptable operation are especially tight, and it is necessary to use a load flow simulation model to make planning decisions that require more exact correlation. In those instances, the study engineer will be challenged to be more exacting about determining the system parameters and developing the system model.

9. Load-flow study example

9.1 General

As anticipated, to illustrate the use of a load flow program, the example system of [Figure 1](#) through [Figure 9](#) will be referenced in the load-flow study example. The example system overall description was provided in [5.2](#), its input data parameters in [Clause 6](#) and [Annex B](#).

Most load flow programs have data checking and analysis routines to help find input data errors. These include a check of the network topology to see that all in-service buses are connected to the swing bus and range checking of certain data items to flag uncharacteristic values.

A fundamental check of the base case is to examine the ability of the load flow solution to converge. As noted in [Clause 7](#), convergence should lead to a very small amount of MW and Mvar mismatch on every bus, where the mismatch is simply the sum of all the active and reactive powers entering the bus. The mismatch should ideally equal zero to satisfy Kirchhoff's laws; however, a small mismatch is acceptable provided its percentage is small in comparison to the total bus load. A small amount of mismatch will not adversely affect the accuracy of the calculated bus voltages. If the load flow solution cannot approach this point for a known normal operating condition, then a problem in the system model is indicated. Scanning of the load flow output to see buses with large values of mismatch or abnormal voltages will often help find the problem area. The problem could be incomplete or inconsistent data. Short low-impedance lines in close proximity with long lines may make convergence difficult. Very low-impedance lines will likely cause convergence problems unless the load flow program contains special logic in the solution techniques to handle them. Engineering judgment is needed to determine whether it is more appropriate to model these elements explicitly or to lump them with adjacent elements.

Most load flow programs have the ability to take a solved load flow case and store all the necessary data, including the solution, in an electronic file. Electronic storage allows easy retrieval of the load flow case to incorporate future changes or to perform outage condition studies.

For each bus, the bus voltage magnitude and angle are calculated. The voltage magnitude may be presented in per unit or kV (or both may be listed). Each branch going from that bus to another bus is listed, providing the MW and Mvar flow (or kW and kvar) on the branch out of the "from" bus. A negative flow means the flow is coming into the "from" bus. For transformers, the tap is also listed. If there is significant mismatch on the bus, it will also be listed. Different programs will use somewhat different formats, but all programs will present basically the same information.

A concise and usually more informative method of presenting load flow results is to display these graphically on the system one-line diagram. System flows can be quickly analyzed from this visual presentation that

relates system configuration, operating conditions, and equipment parameters. Figure 16 displays load flow results in graphical form.

Figure 16 shows the bus voltages and line power flows. Along with the LF output results, the graphical display also shows: system configuration, power supplied by each feeder, shunt load power flows, generator output, transformer tap ratios, and voltage drops on branch elements.

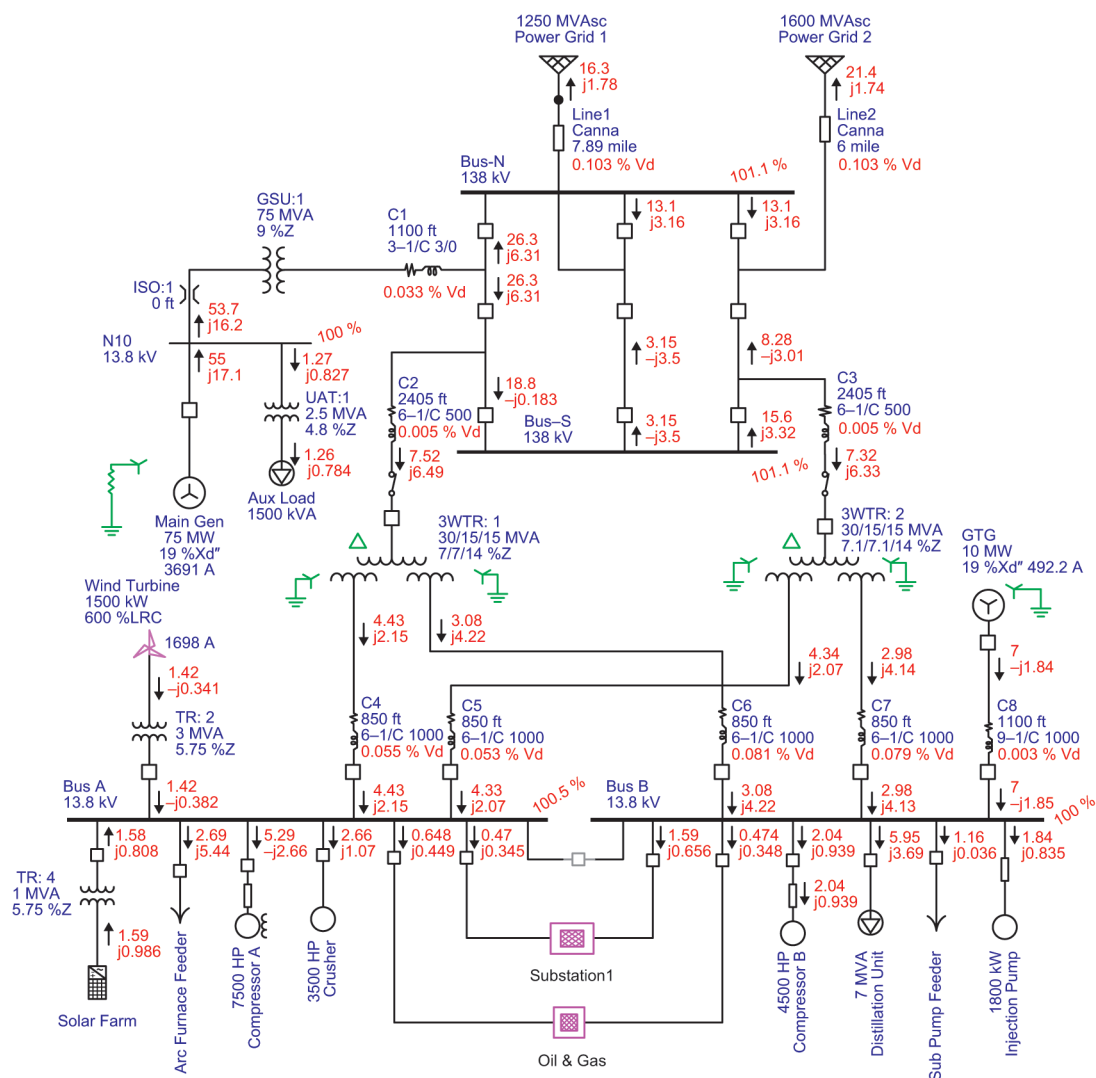


Figure 16—Example of graphical display of load flow results in MW and Mvar

Most commercial load flow programs generate drawings that indicate graphical display of results in a variety of formats. In Figure 16, the power flows are shown near the buses with arrows indicating the direction of the MW and Mvar flows.

Load flow output, as shown in Figure 16, provides an effective means to document study results. Case titles or text on the drawing should indicate the system conditions being analyzed. In this particular case, the “normal” configuration (switching status) is used.

Table 4 presents information which typically depends on the process and system reliability and continuity of operation requirements. If process continuity is of high importance, then the load-flow study must include scenarios which show that the system can properly function under special circumstances like the loss or maintenance of one substation transformer or protective device.

The following major configurations as described in Table 4 will be used in the load-flow study example provided in this clause.

Table 4—Example system switching modes of operation (configurations)

Configuration	Description	Process description
Normal	Tie-breakers normally open. Co-generation operational.	Normal process
FeederOut	Tie-breakers in closed position. Bypass some feeders with alternate transformer supply.	Normal process with potential component failure (loss) or component maintenance
CoGenOff	Co-generator is not operational. Tie-breakers normally open. Minimum system loading and generation.	Turnaround or temporary transition mode of operation

The configurations listed in Table 4 represent only some of the most common configurations used for an industrial power system. The number of switching configurations and operating modes may be large for some systems. Typically “at least one” load flow simulation should be performed for each configuration in a power system.

9.2 Load-flow study scenario considerations

Power system load flow analysis needs to consider all the modes of operation and system switching configurations required to keep continuous operation of critical loads. The system power flow performance can be evaluated by means of different study scenarios or case studies.

The load-flow study scenario selection can be made by considering some of the following aspects:

- Multiple and/or redundant power sources in and out of service (co-gen, peak shaving, emergency power supply, etc.).
- Position (open or closed) of circuit breakers and switches (i.e., main-tie circuit breaker configurations).
- System loading demand should be considered. Both maximum and minimum loading conditions can be useful to determine the system operating limits (i.e., under- and overvoltage conditions).
- Tap positions of on-load-tap-changer transformers. The removal or failure of auto transformers and voltage regulators should be given consideration as additional scenarios. Inadequate transformer tap settings may lead to high-voltage variations and circulating current which will cause unnecessary transformer overheating.
- Branch parameter variation, including the length and impedance tolerance. The effect of operating and ambient temperature on the resistance of cables and overhead lines should be considered.
- Load variation based on changes in voltage and frequency. The study needs to consider the actual load composition including constant kVA, constant impedance, and constant current types of loads. The effect of voltage and frequency variation may also be expressed by using exponential and polynomial load functions.
- Source control modes need to be considered. Voltage control, power factor, Mvar, and swing modes should be considered, including the actual limits applicable to each source as described in 7.8.

- Presence of electronic power converters, var compensators, and other specialized devices that impose non-linearity on operation of the system. Simplified, but adequately accurate models should be incorporated into load flow scenarios.
- Presence of series capacitors (negative impedance) and short cables and bus ducts (small impedances) can be modeled with specially enhanced load flow methods, such as the Adaptive Newton-Raphson method.

When load-flow studies are conducted for industrial applications, there are usually a relatively small, finite number of practical scenarios to consider. It is left to the study engineer to identify those scenarios and formulate the necessary cases for simulation.

For the purpose of the example used for load flow analysis, there are three basic scenarios considered for the load-flow studies, listed in [Table 5](#).

Table 5—Load flow scenarios

Scenario	Loading	Generation	Configuration	Comments
NormalLF	Normal loading	Normal generation	Normal	Base scenario: Normally-open tie breakers. Normal loading and generation. Used to determine normal operating condition load flow results.
MaximumLF	Maximum loading	Maximum generation	FeederOut	Determine if equipment overload occurs with maximum loading and loss of one transformer. Main purpose is to determine equipment overloads.
MinimumLF	Minimum loading	Minimum generation	CoGenOff	With minimum process load and no co-gen. Used to determine if there are any overloads or undervoltage conditions.

Note that positive tolerance adjustments to impedance, resistance, and length were applied with the maximum and normal load flow scenarios. Negative adjustments may be used in some situations with minimum load flow simulations, but are not applied in this example.

On larger systems, there can be a very large number of significant scenarios. Commercial load flow software should be capable of automatically executing studies for every possible scenario and be able to compare the results to find the worst-case results among all cases. This will be further discussed in [Clause 10](#).

9.3 Analysis of load flow results

This subclause provides criteria for the analysis of the load flow results. In the example system, the normal, maximum, and minimum conditions can be analyzed to determine operational limits and problems with equipment capacity.

The analysis of the load flow results may reveal problems as described below:

- Over and undervoltage conditions (i.e., voltage profile, voltage drops)
- Equipment overload/under-utilized conditions (transformer power and current overloads, cable ampacity values exceeded, switchgear continuous current above-rated values, etc.)
- System power factor (operating below desired power factor)
- Incorrect voltage and angle tap settings for looped systems; which may lead to circulating currents and equipment overheating
- Generator/source overload conditions (active and reactive power overloads)

- Spinning reserve limits, total generation, and total load of the system under each configuration
- Steady-state frequency and voltage stability limits (maximum system loading limits beyond which the system voltage and frequency may collapse)

The previous list of items which should be considered in the analysis is only a sample and the comprehensive list will depend on the system design and topology.

9.3.1 Bus voltage profile analysis

Table 6 shows the undervoltage issues (i.e., voltage drops in excess of 5%). Typical over- and undervoltage limits are determined based on the type of system and voltage level. ANSI C84.1 voltage limits are $\pm 5\%$. The minimum normal utilization voltage limit is -10% . That is the voltage drop can be as high as 10% from the bus nominal voltage for some equipment. For this example a voltage variation of $\pm 5\%$ is considered a potential problem.

Table 6—Voltage profile analysis

Bus ID	Nominal kV	Limit violation (%)	Scenario	Condition
Bus 2A	0.48	93.4	MaximumLF	Undervoltage
Bus 3A	0.48	93.6	MaximumLF	Undervoltage
Bus 3B	0.48	93.6	MaximumLF	Undervoltage
Bus 2B	0.48	93.9	MaximumLF	Undervoltage
Bus 1A	4.16	96.1	MaximumLF	Undervoltage
Bus 1B	4.16	96.1	MaximumLF	Undervoltage

Note that overvoltage and undervoltage conditions can be corrected using several techniques, which include the use of synchronous motors, synchronous condensers, capacitor banks, transformer tap adjustments, and increase in reactive power generation, etc.

9.3.2 Equipment overload analysis

The analysis of equipment overloads can be done from the load flow results. Typically, overload conditions will be detected under the conditions with the highest load; however, lightly loaded conditions may also have overload problems if the switching configuration allows for certain equipment to be in operation with unusually high load. The analysis should include all scenarios performed in the load-flow study.

Overload conditions are typically determined by comparing the maximum power or current flow from the load flow scenarios against the equipment maximum rating considering additional available cooling stages (transformers), cable installation and derating procedures, generator maximum power output based on available generation (active and reactive power), etc. Table 7 shows some of the overloads detected by inspecting the load flow results.

Table 7—Overloaded equipment analysis

Element ID	Type	Rating	Loading %	Overload condition	Scenario
TR:1	3 ϕ Xfmr	1 MVA	152.9%	Exceeds maximum MVA rating	MaximumLF
C9	3 ϕ cable	101.937 A	122.9%	Exceeds derated ampacity	MaximumLF
GTG	Generator	10 MW	101%	Reached maximum MW limit	MaximumLF

Other potential overload conditions that may be determined from a typical load-flow study may include:

- Switchgear, MCC, panelboards, switchboards, protective device, and switching elements that have continuous current ratings
- Current limiting reactor with rated full load amp
- Transmission line (overhead bare conductors) ampacity (current-carrying capacity in international standards)
- Capacitor rated current and rated voltage overloads (may require harmonic load flow analysis, but fundamental frequency overload would be determined from basic load flow analysis).
- Inverter/power electronic converters rated current and reactive power limits
- Synchronous motor excitation system limits (over and under excitation limits)
- General source limits like wind-turbine reactive power limits, induction generator overloads, regenerative-drive over and under voltage problems, motor-generator (MG) device power factor problems, etc.

9.3.3 Power flow correction analysis

The purpose of a load flow analysis is not limited to determining equipment overloads and voltage profile problems, but also includes the analysis of the power flows and how they can be improved to reduce system losses and maintain certain operating restrictions under normal operating conditions.

Examples of system power flow improvements include some of the following:

- Power factor correction
- Power flow operating requirements handed down by regulating authorities (reactive power demand based on point of common coupling voltage fluctuations)
- Voltage profile improvement by reactive power support (i.e., the use and selection of static var compensators, capacitor banks, automatic capacitor switching, and adjustable speed drives to reduce reactive power demand)
- Reduction of real power losses in branch elements like cables and transformers by better selection of transformer tap positions, better current limiting device selection

The conclusions listed in [Table 8](#) were made from the load flow analysis in the example system. Only the larger transformer elements are included in the table (i.e., only branch elements with MVA capacity greater than 3 MVA were considered).

Table 8—Power factor analysis results (for some key transformers > 3 MVA)

#	ID	From bus	To bus	Max MVA rating	% PF	Scenario
1	3WTR:2-T	Tertiary winding	N17	28	18.96	MaximumLF
2	3WTR:1-T	Tertiary winding	N15	28	20.62	MaximumLF
3	TR:9	B1	N28	10.5	30.59	MinimumLF
4	3WTR:2-S	Secondary winding	N16	28	64.67	MinimumLF
5	3WTR:1-S	Secondary winding	N14	28	64.84	MinimumLF
6	3WTR:2-P	N13	Primary winding	56	66.98	MaximumLF
7	3WTR:1-P	N12	Primary winding	56	67.01	MaximumLF
8	GSU:1	N9	N10	112	77.5	MinimumLF

Improvements in system operation which can be determined from the load flow analysis are usually made by using the operating modes which are most commonly applied such as the “normal” or “maximum loading” scenarios. Applying system design changes on special operating configurations, which occur infrequently, is not typically required or may not be cost effective. The small improvement in energy consumption or penalty reduction may not justify the additional equipment cost.

The low power factors shown in [Table 8](#) could be corrected using several techniques. The power factor of row 3 in [Table 8](#) can be corrected with the proper sizing of the harmonic filters (which add power factor correction vars) and/or with the reactive power output settings of the synchronous generators and condensers. The lowest power factors in the system ([Table 8](#), rows 1 and 2) may be a result of the improper utilization of the cogenerator reactive power output. If a power factor of 90% or higher is required by the contract with the utility during the entire operational time of the system fed from the three-winding transformers, then some additional reactive power must be provided by the system itself. Changing the output voltage of the cogenerator and/or placing some additional capacitor banks could easily resolve these power factor issues (see [Figure 18](#)).

A load flow scenario with the proper sizing of the harmonic filters and or synchronous condensers is not presented here, but the concept remains the same; the addition of these elements would easily show the improvement in the operating power factor of the feeder branch to the arc furnace.

If capacitor banks would have to be installed and switched on during maximum load conditions, the capacitor location and voltage level could not be determined from load flow power factor correction alone, but harmonic load flow and switching transient analysis are needed as well.

Another element which plays a role in power factor improvement is the adjustable speed drive (or VFD); which operates with an input power factor between 94% and 95%. However, its power factor improvement is for fundamental frequency. Other frequencies and harmonic analysis plus other studies may be required to evaluate the PF improvement of a VFD.

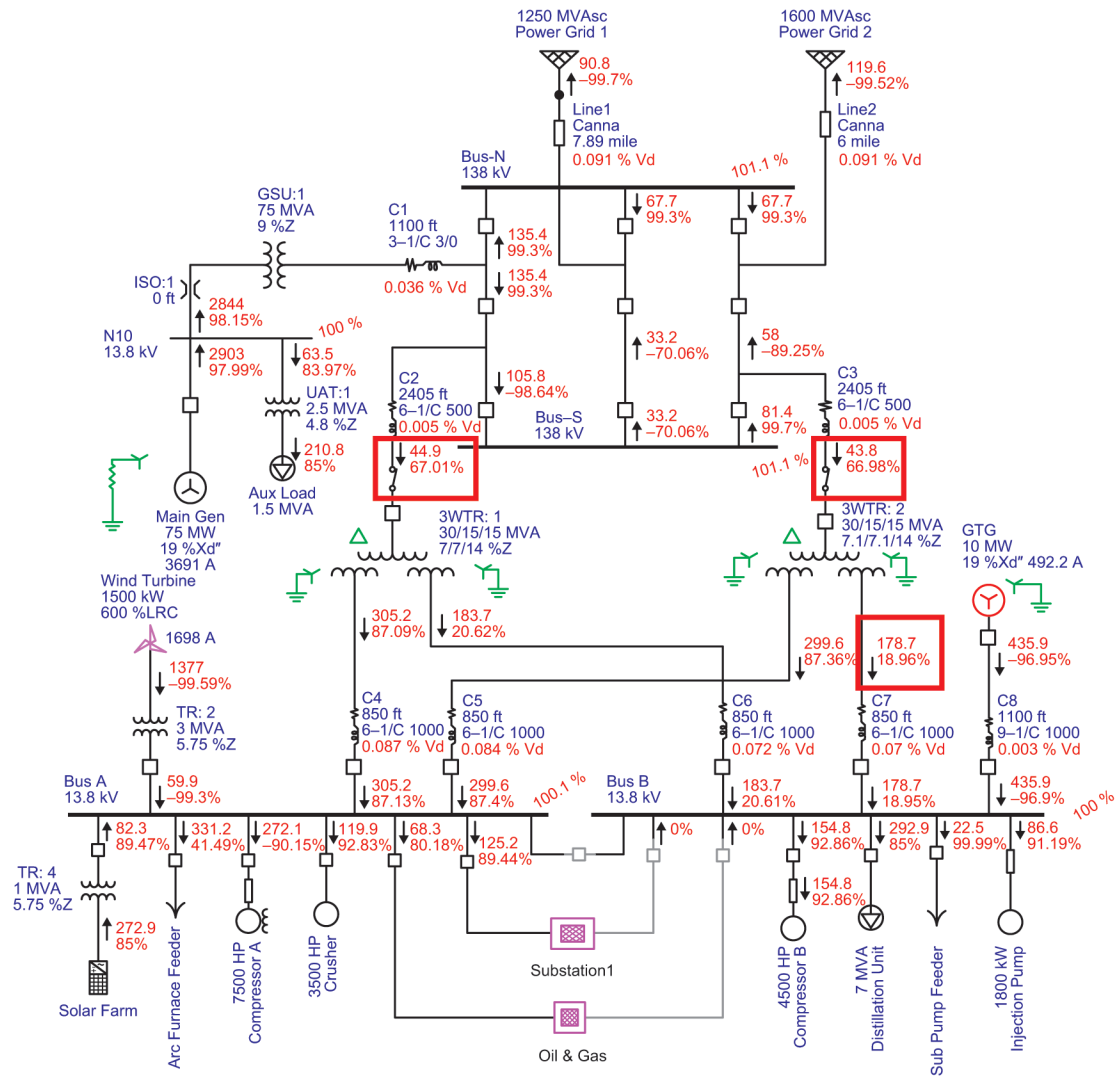


Figure 17—Load flow results in amps and %PF for MaximumLF scenario, without power factor correction

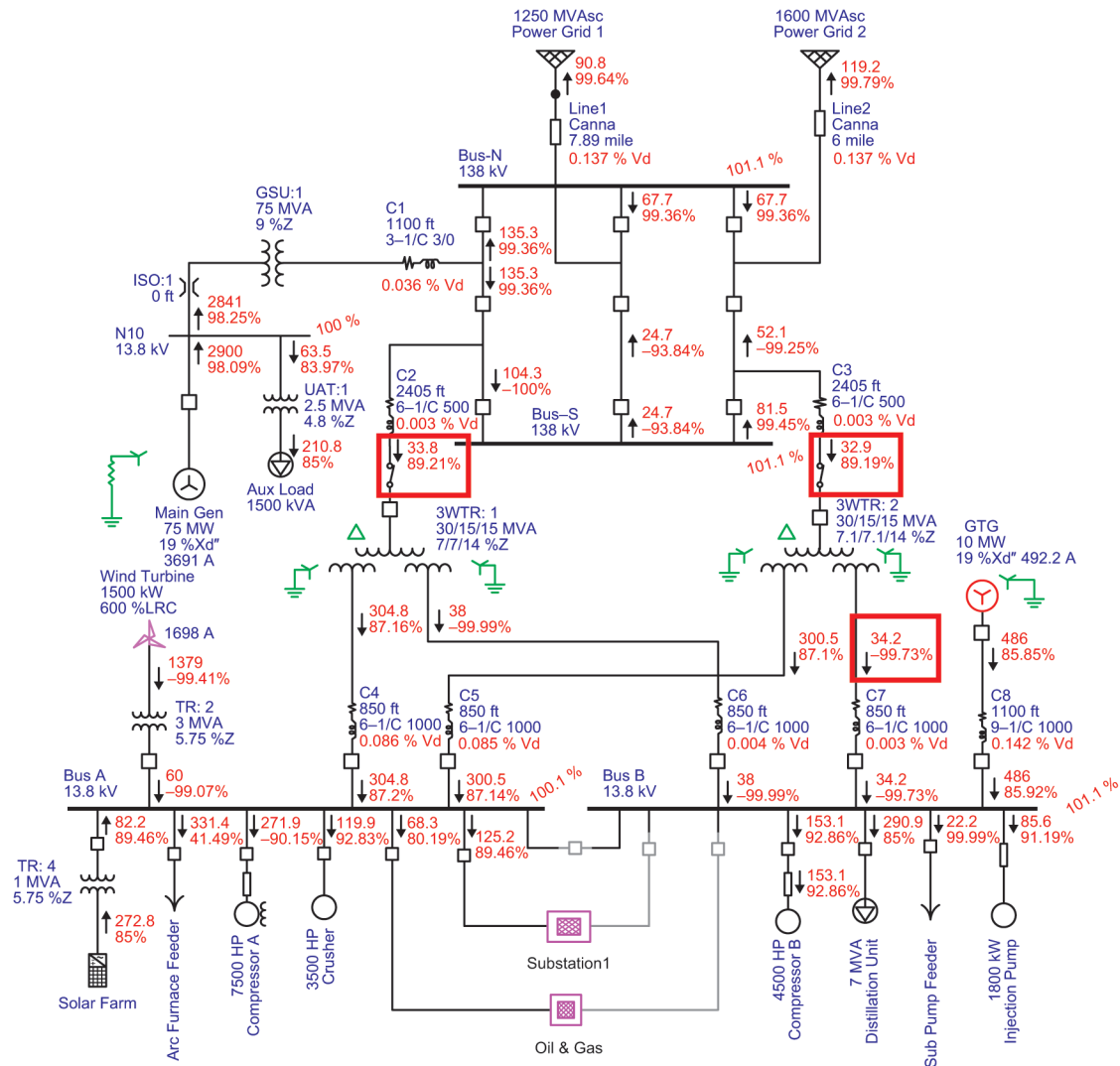


Figure 18—Load flow results in amps and %PF for MaximumLF scenario, with cogen voltage increase for PF correction

Analysis of the system load flow outputs after each set of changes results in the system being gradually tuned to obtain the most efficient and reliable operation. Experience with load flows improves the engineer's ability to make corrections with a minimum number of load flow solutions. However, it is stressed that any change affects the whole system, and a cure at one spot can create unexpected problems at another location in the system. For this reason, it is better not to make too many changes in a single run as the effects on the system may be difficult to understand. Each system change should be documented showing changes made and results obtained in order to keep future changes consistent with improving the system. Furthermore, each system change may also need to be evaluated under short-circuit, harmonics, transients, and switching transients conditions as deemed necessary or applicable. These additional studies further emphasize the need for integrated computer simulation tools.

10. Analysis of load flow results and reports

10.1 Introduction

All the essential output data and results from the analysis must be reported in an organized fashion, describing the parameters for each bus: bus voltages and phase angles, branch flows and voltage drops, load power consumption, and reactive powers. In industrial system studies, the number of cases that must be simulated to assess scenarios of interest is usually finite, and flow diagrams are the most common form of documentation. The challenge for the study engineer is to then recognize when the diagram shows undesirable circuit flows or bus voltages, and to suggest solutions to remediate those issues. Typically, it would be expected that additional simulations be done to demonstrate the efficacy of the suggested solutions.

Flow diagrams are often impractical on larger systems. Instead, the usual practice is to instruct the software to recognized instances where the flow through a path exceeds the rating of that path, or where the voltage on a bus falls outside a specified voltage tolerance for that bus. Then, those “criteria violations” are summarized in a table. In those cases, the concern is not so much for how the criteria violations come about as it is for the fact that they occur, and the job of the study engineer is to find system operating solutions that minimize the number of reported violations.

The report may also flag abnormal operating conditions, such as overloaded cables and over- or undervoltage buses. As an example, operating voltages below a certain threshold, as established by the criteria chosen for the load-flow study, are put in evidence in the report for affected buses, so that corrective steps can be taken. Namely, the regulation features of load tap changers, if present in transformers, can be applied to regulate the bus voltage. Fixed taps can also be used, but their settings must be verified in both maximum and minimum load conditions, to prevent the occurrence of overvoltage.

Table 9, Table 10, and Table 11 show small portions of the load flow reports for each of the scenarios performed in the previous clause for the load-flow study.

10.2 Load-flow study scenarios, study wizard, and result analyzer

Load-flow studies are required to determine the health of the system under various operating conditions which can be numerous for a large industrial system. This will require capabilities to create study scenarios for each condition and save them for future reruns. The list of the relevant study scenarios can be kept in a “study wizard” for one-click execution of all studies.

Analyzing and comparing the results of all studies is very time consuming when the bottom line or lowest voltage results are needed. It is more practical to use comparison tools which would allow for the analysis of multiple simulation results. Tools of this nature would then provide a numerical comparison between results of all load flow scenarios and automatically determine the worst-case result for each of the conditions being analyzed as described in 9.3. Table 12 shows an example of how the output of a multiple result analysis/comparison tool could look like for selected branches.

Table 12 shows that under different situations, the overload in branches would occur during the “MaximumLF” scenario (maximum loading). The comparison tool in this case marks the critical and marginal problem areas visually with a bold font.

The benefits of such analysis/comparison tools are many, but include the reduction in analysis time and cost, and the removal of human error, since the extraction of the violations and problem areas would not be performed manually. Another benefit could be the automatic comparison of the “final recommended” solution against the original load flow results without correction.

Table 9—Load flow for normal loading condition

Bus		Voltage		Generation		Load		Load flow				XFMR %Tap
ID	kV	% mag.	Angle	MW	Mvar	MW	Mvar	MW	Mvar	Amp	%PF	
B1	13.80	99.942	−30.5	0	0	0	0	Bus A	−5.416	252.9	44.3	
								N28	8.217	361.7	30.9	−2.500
								Bus filters	−2.801	117.3	−0.2	
Bus 1A	4.160	100.439	−61.3	0	0	0.004	−0.058	N21	−0.334	79.5	81.4	
								Bus 2A	0.392	83.9	76.4	
Bus 1B	4.160	98.523	−63.1	0	0	1.153	0.271	N22	−1.576	235.7	94.2	
								Bus 2B	0.292	72.3	82.3	
Bus2	13.800	100.003	−30.3	0	0	2.041	0.940	Bus B	−2.041	94.0	90.8	
Bus 2A	0.480	97.943	−92.5	0	0	0.460	0.372	Bus 1A	−0.460	727.0	77.7	
								UPS1	0.030	46.3	80.0	
Bus 2B	0.480	96.492	−94.3	0	0	0.420	0.277	Bus 1B	−0.420	627.0	83.5	
								UPS2	0.008	11.2	90.0	

Table 10—Load flow report for maximum loading condition

Bus		Voltage		Generation			Load			Load flow				XFMR	
ID	kV	% mag.	Angle	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap		
B1	13.80	99.942	−30.5	0	0	0	0	Bus A	−3.256	−7.162	331.2	41.4			
								N28	3.251	9.931	440.0	31.1	−2.500		
								Bus filters	0.004	−2.769	116.6	−0.2			
Bus 1A	4.160	100.439	−61.3	0	0	0.004	−0.058	N21	−2.637	−1.052	410.2	92.9			
								Bus 2A	0.489	0.407	92.0	76.9			
								Bus 1B	1.609	0.596	247.9	93.8			
Bus 1B	4.160	96.059	−65.5	0	0	1.153	0.285	Bus 2B	0.456	0.311	79.7	82.6			
								Bus 1A	−1.609	−0.596	247.9	93.8			
Bus 2A	0.480	93.346	−97.0	0	0	0.485	0.383	Bus 1A	−0.485	−0.383	797.0	78.5			
								UPS1	0.041	0.030	65.3	80.0			
Bus 2B	0.480	93.839	−96.9	0	0	0.452	0.292	Bus 1B	−0.452	−0.292	690.6	84.0			
								UPS2	0.011	0.005	15.4	90.0			

Table 11—Load flow report for minimum loading condition

Bus		Voltage		Generation		Load		Load flow				XFMR	
ID	kV	% mag.	Angle	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
B1	13.800	97.772	−30.0	0	0	0	0	Bus A	−1.639	−2.406	124.6	56.3	
								N28	1.634	5.087	228.6	30.6	−2.500
								Bus filters	0.004	−2.769	116.6	−0.2	
Bus 1A	4.160	98.836	−60.4	0	0	0.004	−0.048	N21	−0.206	−0.105	32.5	89.2	
								Bus 2A	0.202	0.153	35.6	79.7	
Bus 1B	4.160	98.757	−60.4	0	0	0.007	0.048	N22	−0.234	−0.161	39.9	82.4	
								Bus 2B	0.227	0.113	35.7	89.6	
Bus2	13.800	98.160	−30.0	0	0	0.341	0.851	Bus B	−0.341	−0.851	39.1	37.2	
Bus 2A	0.480	97.821	−90.9	0	0	0.201	0.150	Bus 1A	−0.201	−0.150	308.4	80.3	
								UPS1	0.038	0.028	58.3	80.0	
Bus 2B	0.480	97.909	−91.1	0	0	0.227	0.109	Bus 1B	−0.227	−0.109	309.4	90.1	
								UPS2	0.010	0.005	13.8	90.0	

Table 12—Comparison of results for multiple load-flow studies (MaximumLF, MinimumLF, NormalLF)

ID	Type	From bus	To bus	Rating	Allowable	MaximumLF % loading	MinimumLF % loading	NormalLF % loading
C9	Bus A	N21	Cable	3-1/C 4	101.9 A	122.8	9.7	23.8
TR:1	N24	Bus 3A	Transformer 2W	1 MVA	1 MVA	152.9	7.4	76.4

11. Advanced load flow applications

Load flow simulations are sometimes employed for purposes other than simulation of steady-state system performance. These are specialized applications that the study engineer should at least be familiar with.

One application is calculation of short-circuit currents. For conventional load flow analysis it is sufficient to specify only one swing bus in the system. However, it is possible to calculate short-circuit currents by designating a chosen “fault bus” as a swing bus, and specifying that the voltage on that bus must be zero. The simulation will then yield real and reactive power flows that correspond to the currents that will flow to a three-phase short-circuit at that designated bus.

It is important to recognize that this kind of short-circuit calculation may be useful to determine current magnitudes for analyzing relay performance, and also to predict the voltage impact of short-circuits in power quality studies, but because the calculation method does not conform to either IEEE or IEC requirements, the results should not be used to evaluate the application of fault interrupting devices.

A related application is to use load flow simulations to assess the impact of step changes in system loading (or changes in system configuration) on steady-state system voltages. An example of this might be the case where the study engineer wants to know how voltages are affected when a piece of metal enters a rolling mill, when a motor starts, or when a capacitor bank is switched on or off the system. These situations can be analyzed by performing two successive load flow simulations: the first is a steady state load flow simulation of the system immediately prior to the change, while the second is a simulation with the change having been made. To be most accurate, the system model must allow specification of an internal reactance for each generator, and the second simulation must be conducted with the voltage behind that internal reactance (ideally, the saturated, or rated voltage transient reactance, x'_{dv}) held constant at the level determined in the initial simulation (Concordia [B2]). It is important in this type of simulation to consider the inherent or programmed time delays of the equipment. For example, a transformer on-load tap changer is often programmed with a 30 s to 120 s delay, and allowing the simulation software to immediately adjust the tap changer in a motor starting simulation would not be adequate since not enough time has elapsed. It may be advisable to use a dynamic stability software to account for the effect of control and regulation equipment.

12. Features of analysis tools

Many load flow programs are presently available, both in the public domain and as commercial products. Load flow programs differ in the ease of use, program accuracy, program documentation, program sophistication (such as feature set), and of course, cost.

There is a wide range in the level of sophistication in the available programs. There is a corresponding range in the level of user need for this sophistication. The more sophisticated programs may contain several load flow solution techniques allowing for easier solution of a wide range of problems, more data checking activities to help in debugging data input errors, more data handling activities to ease changes to system data or configuration, graphic display of load flow results, ability to handle much larger networks, the modeling of additional power system components, and the incorporation of additional control functions into the solution techniques, as well as time-saving techniques and study case options to generate required scenarios. Complex

industrial and commercial power systems of today, along with their users, need a high level of sophistication from computer power system simulation programs to analyze the power systems.

In the not-too-distant past, load flow programs were limited in the number of buses that could be modeled. The number of buses in the network model determines the size of the bus admittance (Y) matrix that is calculated during the simulation. This limitation was related to the amount of memory available in the computer being used. Computer technology and advanced numerical methods have advanced to the point where memory limitations are no longer a real concern, but software publishers often still impose bus-count limitations as part of a product marketing strategy. The following are the key features of a load flow program that should be used for industrial and commercial applications. These requirements have been separated into minimum requirements for software intended for industrial applications, and optional requirements that offer more flexibility or functionality.

Minimum requirements:

- The software being dimensioned sufficiently to model small and large industrial systems
- Power flow simulation with multiple loading and generation conditions
- Power factor improvement simulation
- User-controlled load flow calculation convergence parameters
- Automatically adjust transformer (two- and three-winding) tap, automatic load tap changer (LTC), and voltage regulator settings
- Automatic generator voltage regulator actions
- Depict power flow results graphically
- Detailed real and reactive power losses calculation and reporting
- Capability to update initial conditions to improve convergence
- Adjust branch impedances on individual and global basis (for length tolerance and resistance temperature variation)
- Save load flow solution parameters for each scenario
- Save changes so that studies can be re-run
- Conduct unlimited “what if” studies within one database
- Calculate power flows, losses, voltage drop, bus voltages, currents, and power factors
- Bus, transformer, line, cable, and generator overload warnings

Optional functionality:

- Load flow database integrated with the databases required for other related studies (including but not limited to short-circuit studies, motor starting studies, stability studies, harmonic studies, etc.).
- Automatically execute simulations for every practical operating scenario to determine all critical and marginal limit violations. Violation alerts ideally should be displayed in alert windows and tabular reports.
- Automatic temperature correction to determine the thermal capacity of circuit elements (mainly branch elements like cables and transformers).
- Modeling of phase-shifting transformers.
- Compare and analyze multiple reports using specific routines.

- Auto-run load flow mode based on system changes.
- Solve either three-phase or single-phase system load flow.
- Update loading for dc load flow calculations. Considers power factor and efficiency at no-load and overload conditions.
- Data exchange (import and export) capabilities to allow data sharing with external applications to minimize or eliminate duplicate data entry. Data transfer can be toward general purpose spreadsheets, databases, and facility design software.

An alternative to in-house use of a load flow program is to use consultants who can do the analysis and present the facility engineer with a complete report, including a technical analysis of the computer output together with their findings and recommendations on system improvement. Consultants have the advantage of having the experience required to efficiently execute studies and correctly interpret results. However, it is still important for the industrial facility engineer to understand the data requirements, how a study is performed, how valid the assumptions are, the results, and how sound the suggested changes to the system are. In addition, a complete copy of the latest project file database (including the associated libraries, warehouse, study scenarios, etc.) should be kept with the facility and maintained using the same priority given to key facility drawings like one-line diagrams and protective device settings. The load flow database contains critical data often needed to perform arc-flash (AF) incident energy calculations using integrated power system analysis software. AF incident energy calculations may need to be updated on a regular basis, which justifies keeping the project file database up to date.

13. Optimal power flow

There are three types of load flow based studies commonly referred to in power system literature as *power flow* (*load flow*), *economic dispatch*, and *optimal power flow (OPF)*. Load flow methods find a mathematical, but not necessarily physically feasible or optimal, solution. Load flow equations themselves do not take account of limitations on generator reactive power limits or transmission line limits, but these constraints can be programmed into many power flow calculation solvers.

In traditional load-flow studies, the final settings of many system control parameters are based on the engineer's experience and judgment. Sometimes an iterative process is required to reach the final overall satisfactory settings. This process can be very exhaustive for large systems. These system control parameters are typically transformer LTC settings, generator MW generation or fuel cost, generator AVR settings or reactive power generations, series and shunt static var compensation device settings, the amount of load shed, and some others. In practice, any of those control settings or any combination of them can be used in a particular system.

Economic dispatch describes a variety of formulations to determine the least-cost generation dispatch to serve a given load with a reserve margin, but these formulations simplify, or sometimes altogether ignore, power flow constraints.

An OPF study can be understood as an intelligent load flow. It employs an optimization technique to automatically adjust the power system control settings while it solves the load flow equation at the same time. Moreover, it allows you to specify a wide range of optimization criteria for your system and enforce limits on system quantities (bus voltage, branch flow, etc.) during the optimization process. These optimization criteria are called objectives, usually the system performance indexes, and the limits are called constraints. There are a variety of formulations with different constraints, different objective functions, and different solution methods that have been labeled optimal power flow.

OPF is utilized for industrial and commercial networks to identify the optimal operating points for MW and Mvar control devices such as generators, load tap changers, and capacitor banks. An OPF study should be performed on a green-field system prior to commissioning, and periodically on a brown-field system depending

on the changes made to major control equipment, such as adding a new generator, upgrading a transformer, addition of capacitor banks, etc.

Criteria for choosing an OPF solver:

- a) Utilization of full ac OPF not based on dc OPF or decoupled ac OPF
- b) Considers voltage magnitude constraints
- c) Considers transmission interconnection or point of common coupling constraints
- d) Includes real and reactive power losses
- e) Includes generator fuel cost
- f) Utilizes, at minimum, interior point optimization technique with the logarithm barrier function and the prime-dual direction searching method for robust solution for large size systems with both equality and inequality constraints

14. Time series (time domain) load flow

Commercial circuit analysis tools have historically provided the capability to analyze the power system at specific snapshots in time. The engineer had to analyze time series data or use operational philosophy to choose specific time instances that correlate to minimum and maximum loading, and/or generation. These simulations provide only a snapshot assessment of the load flow and give only the magnitude of an impact at one instant in time.

More recently, simulation platforms have the capability to perform quasi-static time series simulations or time domain load flow (TDLF). The main advantage of using TDLF simulation is its capability to properly assess and capture the time-dependent aspects of load flow. TDLF produces sequential steady-state power flow solutions where the converged state of an iteration is used as the beginning state of the next. Examples of the time-dependent aspects of load flow include the interaction between the daily changes in load and generation. For systems with interconnected renewables such as solar (PV) panels, daily simulations of PV output and its effects on power distribution systems can be analyzed using more simulation points than simply the maximum and minimum cases. TDLF is useful to assess daily and seasonal variation in power flow penetration caused by renewables installed in industrial facilities. It also provides the benefit of analyzing the impact renewable energy sources have on system voltage and frequency.

TDLF simulations require more data to represent the time-varying generation coincident with time-varying load. The time series data is often difficult to obtain as the measurement equipment at the power distribution feeders and renewable plants will need to be upgraded with higher time resolution capability. The necessary data set can become very large depending on the resolution and length of simulation desired, and simulation processing times can increase quickly and become burdensome. TDLF simulations may also require gathering additional system data including time delay control settings on voltage regulation devices such as capacitors and voltage regulators/load tap changers and more detailed information on the generation profile, substation transformer, and transmission source impedances. The data gathering may be less onerous for continuous process industrial facilities which operate with a constant production rate for most of the year. For such facilities, the major loads that need to be considered for TDLF are heating, cooling, and lighting loads. The time-varying loading of these load types can be easily managed with TDLF tools.

Criteria for choosing a TDLF solver:

- a) Utilizes loading and generation time series data at any resolution and combination of resolutions
- b) Able to solve ac and dc network power flow solution in a non-iterative manner

- c) Able to include events such as breaker switching operation that may happen during the day or as an unplanned outage
- d) Able to use current injection techniques to solve ac unsymmetrical power system network
- e) Able to utilize voltage correction devices, such as load tap changers, and power factor correction devices, such as switched capacitors, during the simulation
- f) Ability to solve for short-term planning period (< 1 year), mid-term planning period (1 year to 10 years), and long-term planning period (> 10 years)
- g) Able to provide output plots as a function of time including voltage, current, power, power factor, energy, etc. at various time aggregations

Not all of these criteria is required for each application. The user must judge which criteria are relevant to the present and anticipated future needs of the facility when selecting software tools to use.

15. Predictive load flow solutions

In order to design, operate, and maintain a power system, one must first understand its behavior. Traditional simulation functions consist of routines that utilize “offline” data for the purpose of engineering analysis of power systems in order to *design* safe and reliable systems. The ability to perform predictive simulation or “what if” studies using “online” or “real-time” operating data is critical to the safe and reliable *operation* of the facility. If offline power systems analysis is conducted prior to any design change or retrofit, it is inferred that online power system analysis is desirable prior to making any operational change. The ability to adequately archive power system operating data must be considered in the new design of a facility, or the available data will prove to require substantial manipulation prior to use in any conventional load flow model, let alone the online power system analysis suggested here.

Predictive load flow requires extensive data processing including data verification, filtering, and remedy actions. Missing data should be either calculated or estimated from telemetered data. As shown in [Figure 19](#), Predictive load flow is capable of acting on data collected from the electrical system reflecting its current status and loads, or on previously collected or historical data.

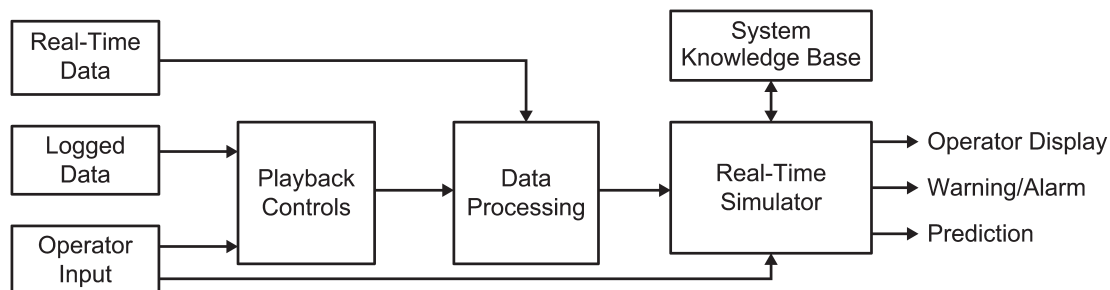


Figure 19—Predictive simulation with online or historical data

Online load flow or predictive load flow uses telemetered or estimated loading, generation, network topology, and operating constraints to provide validation that the system could continue its normal operating condition. Using the operating state of the system as initial condition, predictive load flow allows operators to understand and anticipate the systems reaction before taking an action, such as closing or opening a circuit breaker, or validation of each step in a complex switch plan execution. The results of simulation may indicate that additional action on the system is desired or warranted. In such cases, simulation may be used to successively evaluate an entire series of actions. “What if” studies can be made by simulating virtually any system event and running load flow calculations to determine subsequent voltages and flows. For user convenience, rapid

solution convergence should be obtained through the use of advanced sparse matrix and lower-upper (LU) decomposition methods.

In an electrical power system often data from some network substations are simply unavailable either due to meter problems, or communication failure between the meters and the remote data acquisition equipment, or simply because no metering devices were ever installed. *State estimation* is the process of assigning a value to unknown (missing) system parameters (e.g., voltage magnitude, voltage angle, etc.) based on the measurement (metered) values. In other words, state estimation calculates pseudo-telemetered values. State estimation is combined with load estimation or state and load estimation (SLE) which uses the network topology, switching device configuration status, and engineering properties to calculate, then distribute the resultant system loadings for each relevant device. Using SLE, the entire system estimated load flow can be calculated and used for predictive simulation including, but not limited to, predictive load flow.

16. Conclusions

It should be evident to designers and operators of industrial and commercial power systems, as well as to utility system engineers, that a tool that predicts the actual performance of their electrical systems (under various steady-state operating conditions) is very valuable and essential for the short- and long-term operation of the power systems. That is why load flow is called “the mother of all studies.”

Load flow analysis is used to conduct conceptual design, and to determine equipment size, transformers tap settings, switching interlocks logic, operational limits, etc. This document provides a guideline for this important engineering process. In addition, load-flow studies should be used as the number one tool to validate the electrical network model.

Voltage stress and thermal overload result in degradation of the strength and performance of electrical insulations, which in most cases, are irreversible processes. Insulation damage is one of the main reasons for reduction of equipment life and eventual failure, followed by expensive unscheduled downtimes.

This guideline provides recommendations on how to use power system analysis software to design electrical networks in order to operate within their required limits at any real-time operating conditions. It is therefore essential to study the system to keep the operating voltages within the ideal operating range (e.g., 98% to 102%), within an acceptable range (e.g., 95% to 105%), and within manufacture range (e.g., 90% to 110%).

This document is not recommending the use of any specific power system software.

Annex A

(informative)

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Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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⁴IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

Annex B

(informative)

Example system input data

This annex provides all input tables for the sample system used in this chapter.

Table B.1—Generator data

ID	Rated kV	Rated MVA	Rated PF%	Rated EFF	LF mode	Generator MW	Qmax Mvar	Qmin Mvar	Pmin MW	Xd' %
GTG	13.8	11.765	85	95	PV ^a	10	6.033	−4.14	0	28
Main Gen	13.8	88.235	85	95	PV	75	49.815	−20.835	0	28

^aConstant power output with voltage regulation

Table B.2—Utility source data

ID	Rated kV	LF mode	%V	MVAsc	X/R	R ₁ %	R ₂ %	R ₀ %	X ₁ %	X ₂ %	X ₀ %
Power Grid 1	138	Swing	101	1250	35	0.228	0.228	0.228	7.99	7.99	7.99
Power Grid 2	138	Swing	101	1600	25	0.249	0.249	0.249	6.24	6.24	6.24

Table B.3—Two-winding transformer data

ID	Rated MVA	Primary kV	Secondary kV	Z ₁ %	X ₁ /R ₁ ratio	Fixed tap %	Connection primary-secondary	Angle degree	Max MVA ^a
GSU:1	75	138	13.8	9	3.09	5	ΔY	30	112
TR:1	1	13.8	0.48	5.75	14.23	0.0	ΔY	30	1
TR:2	3	0.6	13.8	5.75	14.23	0.0	ΔY	30	4.2
TR:3	1	13.8	0.48	5.75	14.23	0.0	ΔY	30	1
TR:4	1	4.16	13.8	5.75	14.23	0.0	ΔY	30	4.2
TR:5	2	13.8	4.16	6.52	12.5	0.0	ΔY	30	7
TR:6	2	13.8	4.16	6.41	12.25	0.0	ΔY	30	7
TR:7	1	13.8	4.16	5.5	5.79	0.0	ΔΔ	0	1
TR:8	1	13.8	4.16	5.5	5.79	0.0	ΔY	30	1
TR:9	7.5	13.8	4.16	6.4	14.23	−2.5	ΔY	30	10.5
TR:10	1	4.16	0.48	5.44	5.79	0.0	ΔY	30	1.288
TR:11	1	4.16	0.48	5.63	5.79	0.0	ΔY	30	1.288
UAT:1	2.5	13.8	4.16	4.8	4.7	0.0	ΔY	30	2.5

^aTransformer maximum loading is accomplished with additional cooling stages.

Table B.4—Cable impedance data (impedances in Ohms per 304.8 m (1000 ft) and sizes)

ID	From bus	To bus	Rated kV	Length m (ft)	Size AWG/kcmil	Insulation type	Con. type	#C/pt ^a	R _i (Ω)	X _i (Ω)	Base temp °C	Max. temp °C
AF ^b	Bus A	B1	15	576 (1890)	500	Rubber 2	Cu	1	0.051	0.077	75	75
C1	N9	N3	25	335 (1100)	3/0	EPR	Cu	1	0.087	0.115	90	75
C2	N6	N12	138	733 (2405)	500	EPR	Cu	2	0.035	0.078	90	75
C3	N8	N13	138	733 (2405)	500	EPR	Cu	2	0.035	0.078	90	75
C4	N14	Bus A	15	259 (850)	1000	EPR	Cu	2	0.022	0.071	90	75
C5	N16	Bus A	15	259 (850)	1000	EPR	Cu	2	0.022	0.071	90	75
C6	N15	Bus B	15	259 (850)	1000	EPR	Cu	2	0.022	0.071	90	75
C7	N17	Bus B	15	259 (850)	1000	EPR	Cu	2	0.022	0.071	90	75
C8	N18	Bus B	25	335 (1100)	1000	EPR	Cu	3	0.022	0.071	90	75
C9	Bus A	N21	15	401 (1316)	4	Rubber 2	Cu	1	0.321	0.0594	75	75
C10	Bus B	N22	15	401 (1316)	4	Rubber 2	Cu	1	0.321	0.0594	75	75
C11	MCC2	B-10	0.6	99 (325)	1	Rubber	Cu	1	0.16	0.038	75	75
C12	Bus A	N24	15	274 (900)	25	XLPE	Cu	1	0.927	0.151	90	75
C13	Bus B	N25	15	274 (900)	25	XLPE	Cu	1	0.927	0.151	90	75
C14	Bus 3A	N26	1.0	6 (20)	16	XLPE	Cu	1	1.47	0.091	90	75

Table continues

Table B.4—Cable impedance data (impedances in Ohms per 304.8 m (1000 ft) and sizes) (continued)

ID	From bus	To bus	Rated kV	Length m (ft)	Size AWG/kcmil	Insulation type	Con. type	#C/ph ^a	R _i (Ω)	X _i (Ω)	Base temp °C	Max. temp °C
C15	Bus 3B	N27	1.0	6 (20)	16	XLPE	Cu	1	1.47	0.091	90	75
Cable1	Bus2	Compressor B	15	30 (100)	6	Rubber 2	Cu	1	0.051	0.063	75	75
EC1	Bus 3A	Pump D	1.0	15 (50)	95	XLPE	Cu	1	0.248	0.085	90	75
EC2	Bus 1B	Pump B	5.0	137 (450)	3/0	EPR	Cu	2	0.081	0.037	90	75
EC3	Bus B	Injection Pump	15	30 (100)	25	XLPE	Cu	1	0.927	0.151	90	75
EC4	Bus 2A	Fire Control A	0.6	45 (150)	10	XLPE	Cu	1	4.265	0.109	90	75
EC5	Bus 2B	Fire Control B	0.6	15 (50)	10	XLPE	Cu	1	4.265	0.109	90	75
EC6	Bus 1B	Pump C	5.0	137 (450)	3/0	EPR	Cu	2	0.081	0.037	90	75
EC7	Bus 3A	HVAC 1	0.6	53 (175)	6	THHN	Cu	1	0.049	0.064	75	75
EC8	Bus 1B	Pump A	5.0	137 (450)	3/0	EPR	Cu	2	0.081	0.037	90	75
EC9	Bus 3B	Water Injection A	0.6	99 (325)	300	THHN	Cu	1	0.045	0.051	75	75
EC10	Bus 1A	Compressor C	5.0	107 (350)	3/0	EPR	Cu	2	0.081	0.037	90	75
EC11	Bus A	Compressor A	15	237 (777)	2/0	EPR	Cu	1	0.108	0.095	90	75
EC12	N28	Arc Furnace Load	15	139 (455)	1/0	EPR	Cu	1	0.147	0.047	90	75
EC13	Bus 3B	Seawater Lift Pump	0.6	45 (150)	120	XLPE	Cu	1	0.212	0.08	90	75

Table continues

Table B.4—Cable impedance data (impedances in Ohms per 304.8 m (1000 ft) and sizes) (continued)

ID	From bus	To bus	Rated kV	Length m (ft)	Size AWG/kcmil	Insulation type	Con. type	#C/ph ^a	R _i (Ω)	X _i (Ω)	Base temp °C	Max. temp °C
EC14	Bus 3B	Forced Draft Fan	1.0	6 (20)	70	XLPE	Cu	3	0.342	0.087	90	75
EC15	Bus 3A	Feedwater Pump	1.0	15 (50)	70	XLPE	Cu	1	0.342	0.087	90	75
EC16	Bus 3A	Water Injection B	0.6	99 (325)	300	THHN	Cu	1	0.045	0.051	75	75
EC17	Bus 1A	CAP1	5.0	733 (2405)	6	Rubber	Cu	2	0.51	0.053	75	75
EC18	Bus 3A	ID Fan	1.0	6 (20)	70	XLPE	Cu	3	0.342	0.087	90	75
EC19	Bus 1B	CAP2	5.0	733 (2405)	6	Rubber	Cu	2	0.51	0.053	75	75
SPF ^c	Bus B	N30	5.0	3 (10)	1	EPR	Cu	1	0.184	0.035	90	75
SC ^d	N29	VFD-MTR	5.0	991 (3250)	1	EPR	Cu	1	0.184	0.035	90	75
NOTE—Susceptance values for all cables are negligible and not used in this example.												

^aNumber of conductors per phase^bArc furnace feeder^cSub pump feeder^dSubmarine cable

Table B.5—Transmission line data (impedance in Ohms per mile)

ID	From bus	To bus	Rated kV	Length, km (mile)	Size kcmil	Connection type	R_1 (Ω)	X_1 (Ω)	Y_1 μ Siemens/km (mile)	Base temp $^{\circ}\text{C}$	Max temp $^{\circ}\text{C}$	Phase	Allowed ampacity
Line1	N1	N4	138	12.69 (7.89)	397.5	AI	0.117	0.311	22.608 (14.048)	25	75	3	640.1
Line2	N2	N5	138	9.65 (6)	397.5	AI	0.117	0.311	22.608 (14.048)	25	75	3	640.1

Table B.6—Three-winding transformer data

ID	Prim. kV	Sec. kV	Ter. kV	Prim. MVA rating ^a	Sec. MVA rating	Ter. MVA rating	Prim.- sec. Z1% ^b	Prim.- ter. Z1%	Sec.- ter. Z1%	Prim.- sec. X/R	Prim.- ter. X/R	Sec.- ter. X/R	Winding ^c	Phase shift prim.-sec.	Phase shift sec.-ter.
3WTR:1	138	13.8	13.8	30/56	15/28	15/28	7	7	14	25	25	25	ΔYY	-30	-30
3WTR:2	138	13.8	13.8	30/56	15/28	15/28	7.1	7.1	14	25	25	25	ΔYY	-30	-30

^aPrimary, secondary, and tertiary MVA rating is expressed as base MVA/maximum MVA (considering additional cooling stages).^bPrimary winding base MVA was used to express impedance in %.^cPrimary-secondary-tertiary connections.

Table B.7—Induction motor data

ID	Rated HP	Rated kV	Rated RPM	Qty	PF @ 100%	PF @ 75%	PF @ 50%	EFF @ 100%	EFF @ 75%	EFF @ 50%	NLA %	PF @ NL	Loading % (Hp/kW) max./norm./min.
Compressor B	4500	13.2	1800	1	92.83	92.46	89.72	97.99	98.58	99.03	18.24	0.17	100/60/10
Compressor C	1000	4	1800	1	88.32	86.57	80.57	96.34	97.3	98.06	27.95	0.5	70/0/0
Condenser A	50	0.46	1800	5	83.73	79.4	69.02	90.63	92.41	93.5	42.27	2.87	60/50/80
Condenser B	60	0.46	1800	5	90.82	90.82	90.82	91.68	91.68	91.68	0	90.82	60/50/80
Crusher	3500	13.2	1800	1	92.83	92.46	89.72	97.99	98.58	99.03	18.24	0.17	100/100/10
Drill Motor	1500	4	1800	1	88.32	86.57	80.57	96.36	97.21	97.99	27.95	0.5	100/90/60
Feedwater Pump	100	0.46	1800	1	91.75	91.75	91.75	92.81	92.81	92.81	0	91.75	100/100/10
Forced Draft Fan	150	0.46	1800	1	80	80	80	92.81	92.81	92.81	0	91.75	100/100/10
HVAC 1	10	0.46	1800	6	91.75	91.75	91.75	92.81	92.81	92.81	0	91.75	100/100/10
HVAC 2	15	0.46	1800	1	87.51	87.51	87.51	86.7	86.7	86.7	0	91.75	100/100/10
ID Fan	150	0.46	1800	1	91.75	91.75	91.75	92.81	92.81	92.81	0	91.75	100/100/10
Injection Pump	1800	11	3600	1	91.18	89.86	85.89	95.5	99.4	99.58	0	77.96	100/98/0
Pump A	450	4	1800	1	89.85	88.26	82.73	94.04	94.86	95.62	26.63	1.02	100/100/0
Pump B	500	4	1800	1	89.85	88.26	82.73	94.04	94.86	95.62	26.63	1.02	100/100/0
Pump C	500	4	1800	1	89.85	88.26	82.73	94.04	94.86	95.62	26.63	1.02	100/100/0
Pump D	175	0.46	1800	1	80	80	80	85.1	85.1	85.1	0	91.75	100/100/10
Seawater Lift Pump	75	0.44	1800	2	91.42	91.42	91.42	92.39	92.39	92.39	0	92.02	100/0/0
Water Injection A	60	0.46	1800	5	80	79	75	91.68	91.68	91.68	0	91.75	100/100/10
Water Injection B	60	0.46	1800	6	82	80	80	91.68	91.68	91.68	0	91.75	100/100/10

Table B.8—Synchronous motor data

ID	Rated HP	Rated kV	Rated RPM	Qty	Rated PF%	Rated EFF%	PF @ 100%	PF @ 75%	PF @ 50%	EFF @ 100%	EFF @ 75%	EFF @ 50%	Loading % (Hp/kW) max./norm./min.
Compressor A	7500	13.2	900	1	−90%	95.6	−90	−88	−86	95.6	95	94	100/90/40

Table B.9—Motor operated valve data (MOV)

ID	Rated HP	Rated kV	Rated RPM	Qty	Rated PF%	Rated EFF%	Status
Fire Control A	1	0.46	1800	1	81.0	64.8	Opening
Fire Control B	5	0.46	1800	1	84.9	72.4	Opening

Table B.10—Load data

ID	Rated kV	Rated kVA	Rated PF	Constant MW%	Constant Z%	Phases	Loading % (kVA) max./norm./min.
Aux Load	4.16	1500	85	80	20	3φ	100/100/50
Distillation Unit	13.8	7000	85	80	20	3φ	100/100/0
Flare System	0.44	37.5	80	100	0	3φ	100/80/0
Receptacles A	0.48	400	80	80	20	3φ	100/100/0
Receptacles B	0.48	350	80	80	20	3φ	100/100/0
Turbine CP	0.44	37.5	80	100	0	3φ	100/80/0
Arc Furnace Load	4.16	11260	30	0	100	3φ	100/80/50
Lighting	0.48	30	83	0	100	3φ	100/60/90
Server Racks	0.48	35	85	0	100	3φ	100/60/90

Table B.11—Adjustable speed drive (VFD) data

ID	Rated HP	Rated kV in	Rated kV out	Rated Hz in	Rated Hz out	Rated PF% out	Rated PF% in	Rated EFF%	Freq. max./min. %
ASD-12P	1000	4.16	4.16	60	60	74.57	71.36%	95%	150/0

Table B.12—Wind turbine generator data

ID	Rated kV	Rated MVA	Rated PF%	Rated EFF	Operation mode	Generator MW	Qmax Mvar	Qmin Mvar
Wind Turbine	0.6	1.765	85	95	PV ¹	1.5	0.9	−0.9

Table B.13—Protective device configuration

Element ID	Type	Normal	CoGenOff	FeederOut
7B9–1-2	HVCB	Closed	Closed	Open
CB:6	HVCB	Open	Open	Open
CB:9	HVCB	Closed	Open	Closed
CB:15	HVCB	Closed	Closed	Open
CB:18	HVCB	Closed	Closed	Open
CB20–2	HVCB	Open	Open	Closed
CB13	LVCB	Open	Open	Closed
CB14–1	LVCB	Closed	Closed	Open
CB19–2	LVCB	Open	Open	Open
NOTE—PD Configurations which are not listed above are considered to be normally-closed in all configurations.				

Table B.14 presents an example of the drawing format symbols used for the example presented in Clause 5. Table B.14 shows the available IEEE Std 315-1993 symbols. The table also shows which element symbols are not available in the standards and which elements may require more than one symbol for proper graphical representation in the computer software (i.e., compound symbols).

Table B.14—Element symbols used for computer software example









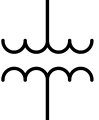


























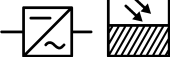











Software symbol	IEEE Std 315-1993 symbol	Description	Software symbol	IEEE Std 315-1993 symbol	Description
		Induction machine			Phase current transformer
	N/A	Lumped load: motor + static loads			Overcurrent relay
		Two-winding transformer		N/A	Ground current transformer
		Synchronous generator		FL	Harmonic filter
		Synchronous motor			Switch
	N/A	Utility power supply		N/A	Static load
		Cable		N/A	Adjustable speed/frequency drive
		Wind turbine generator			Shunt capacitor
		Transmission line			Contactor
		High-voltage circuit breaker			Overload heater
		PV array: solar panels + inverter		N/A	In-line overload relay
		Low-voltage circuit breaker			Fuse

Table continues

Table B.14—Element symbols used for computer software example (*continued*)

Software symbol	IEEE Std 315-1993 symbol	Description	Software symbol	IEEE Std 315-1993 symbol	Description
		Motor operated valve		N/A	Panelboard
	N/A	Uninterruptible power supply		N/A	Remote connector
	N/A	Composite network: nested or layered one-line diagram			

Consensus

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